
Proceedings of:

Precision Interferometric Metrology

2010 Summer Topical Meeting

June 23 to 25, 2010

*The Crowne Plaza Tennis and Golf Resort
Asheville, North Carolina*

The American Society for Precision Engineering (ASPE) is a multidisciplinary professional and technical society concerned with research and development, design, manufacture and measurement of high accuracy components and systems. ASPE activities encompass relevant aspects of mechanical, electronic, optical and production engineering, physics, chemistry, and computer and materials science. Membership is open to anyone interested in any aspect of precision engineering.

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Preface

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2010 Summer Topical Meeting

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*4th Meeting on
Precision Interferometric Metrology
June 22 to 25, 2010*

Meeting Schedule

	Tuesday 22		Wednesday 23		Thursday 24		Friday 25
		7:30	Registration and Continental Breakfast	7:30	Registration and Continental Breakfast	7:30	Registration and Continental Breakfast
		9:00	TECHNICAL SESSION I	8:30	TECHNICAL SESSION V	8:30	TECHNICAL SESSION VIII
		10:00		10:00		10:00	
10:00	PRE- CONFERENCE DAY OF UNC CHARLOTTE LABS TOUR		Coffee Break		Coffee Break		Coffee Break
		10:30	TECHNICAL SESSION II	10:30	TECHNICAL SESSION VI	10:30	TECHNICAL SESSION IX
		12:00		12:30		12:15	
			Lunch		OPEN DISCUSSION AND FREE TIME		Lunch
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		3:30	TECHNICAL SESSION IV				
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		8:00	WELCOME BARBEQUE	9:00	OPEN FORUM		

Foreword

Applications such as flat panel displays, IC manufacturing, automotive systems and basic science are driving demand for lower uncertainty measurements in ever more challenging environments. This meeting will cover new developments in interferometric metrology — including new concepts and analyses, instrument development and application examples. In addition to paper sessions, there will be open discussion sessions and opportunities to make brief informal presentations on a variety of topics of interest. The talks will cover a broad range of technologies and highlight potential areas for future development.

The objective of this meeting is to bring together specialists and practitioners from industry, government and academia to provide a forum for the exchange of ideas. The meeting will emphasize discussions as much as the presentations and the participants are encouraged to identify areas needing further research.

The 4th ASPE Topical meeting on Precision Interferometric Metrology will follow the format of its successful predecessors — most recently in Middlefield, CT in 2005 — with meetings in the morning, an evening Open Forum, and an afternoon free to discuss technical details, play sports, walk, shop, or just relax.

2010 Summer Topical Meeting Program Committee:

Meeting Co-Chairmen:

Chris J. Evans and Peter J. de Groot
Zygo Corporation

Angela D. Davies
University of North Carolina at Charlotte

Scientific Committee:

K-F Beckstette, Carl Zeiss Jena, Germany
B. Dörband, Carl Zeiss SMT AG, Germany
W. T. Estler, National Institute of Standards and Technology, USA
G. Forbes, QED, Australia
G. Häusler, University of Erlangen-Nuremberg, Germany
O. Lay, Jet Propulsion Laboratory, USA
H. Ottevaere, Vrije Universiteit Brussel, Belgium
G. Owen, Agilent, USA
R. Parks, University of Arizona, USA
J. Schmit, Veeco, USA

Technical Sessions

Session I

Wednesday, June 23, 2010, 9:00 AM - 10:00 AM

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1. **Welcome Words**
2. **Introductory Remarks**
W. T. Estler, ASPE President (Retired, National Institute of Standards and Technology)
3. **Keynote Address**
The Fusion of Interferometry and Microelectronics – Personal Views
John H. Bruning (Retired, CEO of Corning Tropel Corporation)

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Open Forum with Bar

A tradition at ASPE's Topical Meetings on interferometry is an evening session of free flowing discussion, short reports on the latest results, pleas for help on intractable problems, and provocative presentations on needs and technical directions in the field. Bring a couple of viewgraphs and come prepared to participate.

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Technical Papers



A S P E

PICOMETER DISPLACEMENT METROLOGY FOR FUNDAMENTAL STANDARDS

John R. Lawall

National Institute of Standards and Technology
Gaithersburg, Maryland 20899-8422

The SI (Système International d'Unités) defines three mechanical base units (the meter, the kilogram, and the second), and one electrical base unit (the ampere). By agreeing on a common choice of base units, scientists and engineers are able to relate physical measurements made in different laboratories at different times to one another. This fundamental fact, often taken for granted, is crucial to modern manufacturing and commerce.

The actual definition of the ampere, involving the force per unit length of two current-carrying parallel wires spaced by one meter, is too cumbersome for practical realization. In practice, the link between mechanical units and electrical units made in national standards laboratories involves a "calculable capacitor" (CC) [1], a set of electrodes constructed such that a linear displacement of one electrode causes a proportional change in an electrical capacitance, with the constant of proportionality calculable from first principles. In short, the Farad is realized directly in terms of the meter. The CC then allows the realization of the other SI electrical units, such as charge, voltage, and magnetic field, as well as calibration of quantum standards of voltage and resistance. It is also an input into measurements which are likely to replace the current (artifact) definition of the kilogram with a non-artifact definition based on the equivalence of electrical and mechanical power.

The current NIST calculable capacitor is over forty years old. It employs a movable electrode with a travel range of 250 mm, and the optical interferometric technique employed to monitor the motion of the electrode imposes severe practical limitations. In the meantime, enormous advances have been made in laser technology and interferometry, the SI meter has been redefined, and frequency comb techniques have revolutionized optical frequency measurement and synthesis. For these

reasons, NIST has recently undertaken the construction of a new calculable capacitor. The key theme to the new CC is to dramatically reduce the overall size, while exploiting the advances made in optical interferometry to achieve the picometer-level accuracy necessary to surpass the present instrument.

Thus, the new capacitor employs a maximum electrode displacement of 5 mm, in conjunction with tunable laser Fabry-Perot interferometry techniques demonstrated already [2]. In this new work, ultranarrow linewidth fiber lasers at 1560 nm are employed. The mobile electrode incorporates one mirror of a Fabry-Perot cavity, and as the electrode is moved, the cavity resonance frequencies change. Two fiber lasers are locked to different cavity modes, and by measuring the frequency difference between the lasers, the cavity free spectral range can be inferred with a statistical uncertainty below 1.7×10^{-8} . Next, a third fiber laser is frequency-doubled and locked to a rubidium vapor cell reference, allowing the absolute frequency of a cavity resonance to be measured as well; this allows the cavity order numbers to be deduced, and provides an invaluable check on systematic errors. In a final step, the rubidium reference will be supplemented by a frequency comb, whose optical frequency output will be locked to a cesium clock.

RANGE-GATED METROLOGY: AN ULTRA-COMPACT SENSOR FOR POINT-TO-POINT DISPLACEMENT AND DISTANCE MEASUREMENT

**Oliver P. Lay, Bart Bortnik, Serge Dubovitsky, Kurt Liewer,
Daniel Shaddock, Chris Woodruff
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109-8099**

Point-to-point laser metrology systems can be used to monitor and control structures with nanometer precision. Examples include large optical telescopes and silicon lithography machines. These sensors usually measure the relative optical phase between a beam propagating to a remote target, and a reference beam returned from the sensor head. The two optical returns must be carefully isolated from each other to avoid cyclic error from cross-talk. Previous systems have used different polarizations for the two beams or spatial masking to achieve the separation, resulting in sensor heads that are relatively large and that have multiple optical inputs and outputs. The use of point-to-point laser metrology has therefore been limited to applications where only a few gauges are needed and there is sufficient space to accommodate them.

In a Range-Gated Metrology system, the target and reference returns are isolated based on their different propagation times. This is achieved by adding a Pseudo-Random Noise (PRN) modulation to the outgoing laser light. After detection, this PRN code is demodulated using an FPGA, prior to the standard measurement of optical phase. By changing the relative delay for the PRN demodulation, we can select the propagation time for the optical phase measurement. The range-gating process maintains the optical coherence of the signals, and nanometer precision is preserved. The major advantage of this approach is that we can use a simple fiber optic collimator as the sensor head, with the reference return provided by either the fiber tip (simplest) or from the flat side of a plano-convex lens (best performance). The target return is from a corner cube retro-reflector. A fiber collimator can be made much smaller than the previous designs, making it much easier to integrate unobtrusively into the article under test. The single fiber input/output

also makes it much easier to multiplex many sensor heads together.

A number of Range-Gated Metrology systems have been built and tested at JPL, using FPGAs clocked at 250 MHz to generate the PRN code, demodulate the return signals and make the phase measurements. Nanometer precision has been demonstrated at update rates of up to 5 kHz. In addition to displacement measurements, we have implemented absolute ranging with an accuracy of ~ 5 microns using the MSTAR phase modulation approach. We have also demonstrated both time multiplexing, using a fast fiber optic switch, and delay multiplexing using different lengths of fiber to connect the sensor heads. A sensor head has been built into a 1.5-m 'active strut' whose length can be stabilized to the nanometer level in the presence of thermal and load variations using a PZT actuator. We have also created a 'snap-on' metrology system in which magnetically-mounted collimators can be used to conveniently monitor path lengths in a lab environment.

SENSITIVITY ANALYSIS OF PERIODIC ERROR IN HETERODYNE INTERFEROMETRY

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University of Florida
Gainesville, FL, USA

1. INTRODUCTION

Heterodyne displacement measuring interferometry offers high resolution, high accuracy displacement measurement for non-contact applications. However, the accuracy is limited by non-linearities, or periodic errors, which depend on misalignments in the optical setup [1-19]. These errors are non-cumulative in nature and repeat with each unit wavelength change in the optical path. Apart from periodic errors, there are also other sources of error which are not periodic in nature, such as cosine error, Abbe error, variations in refractive index, thermal deformations, beam shear, non-planar wave-fronts, and wavelength instability of the laser source [8].

The purpose of this study is to complete a sensitivity analysis using the analytical periodic error model from Cosijns et al. [9]. Sensitivity analysis is used to study how the uncertainty in model output is related to the uncertainty in the input parameters [20-22]. Factor prioritization provides an estimate of which input parameter, if fixed, would result in the greatest reduction in output variation. In this way, the input parameters may be sorted in order of importance and it is then possible to concentrate efforts on accurately measuring the important parameters while ignoring the less important ones. Another approach is factor fixing. If the effect of an input (over its range of uncertainty) on the output is negligible, the value of this input can be fixed at any value over its range. In this case, the input variable is non-influential on the model output which enables model simplification.

While a gradient-based local sensitivity approach does provide an estimate for the periodic error dependence on setup misalignments, it does not account for the associated uncertainties. In order to provide a better estimate of model sensitivity, global sensitivity techniques are used here. Variance-based global sensitivity analysis methods

explore the space of input parameters by selecting a judicious number of randomly selected data points from the input parameter space and provide a more informative and robust estimate of the behavior of the model output with respect to variation in the model input [20]. In this study, a variance-based Monte Carlo approach is used to estimate both the individual and total effect Sobol' sensitivity indices for each of the model inputs [20, 24-25]. The study reveals that rotational misalignment of the polarizing beam splitter, α , the rotational misalignment of the mixing polarizer, θ , and non-orthogonality, β_{err} , between the two ideally linearly polarizations laser frequencies are most influential on the output uncertainty.

Contour plots are provided for a range of uncertainties in linear polarizer angle, non-orthogonality, and polarizing beam splitter angle to estimate the expected periodic error for a selected combination of uncertainties. Also, a higher-order regression fit is applied to the expected periodic error data to provide a closed-form expression for periodic error as a function of the uncertainties in the optical setup.

2. PERIODIC ERROR FORMULATION

Figure 1 shows a single pass interferometer setup. For the ideal case (panel a), the two coherent, collinear, orthogonally polarized laser frequencies, f_1 and f_2 , are perfectly separated at the polarizing beam splitter and are directed into the reference and measurement (where the Doppler shift, f_d , occurs during motion) arms of the interferometer. However, due to imperfect optical performance (panel b) there is leakage of each frequency into both the measurement and reference arms. This frequency leakage may occur due to: non-orthogonality of the two frequencies emitted from the laser source; rotational misalignment of the laser beam with respect to the polarizing beam splitter (PBS); ellipticity of the polarization states; different transmission coefficients for the individual laser beams at the PBS; and rotational misalignment

of the polarization axes with respect to the mixing polarizer. Ghost reflections, nonlinearities in the phase measuring electronics, and beam shear have also been found to induce periodic errors.

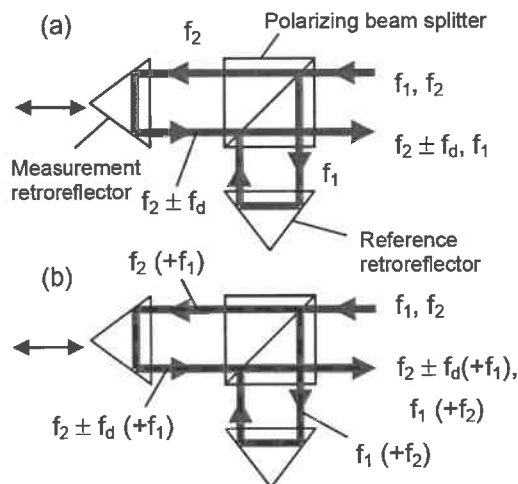


FIGURE 1. Schematics for (a) ideal heterodyne interferometer behavior; and (b) frequency leakage. The two frequencies, f_1 and f_2 , are ideally linearly polarized and orthogonal. This enables the polarizing beam splitter to separate them based on their polarization state [13].

Stone and Howard [11] described a Jones matrix calculus method for estimating periodic error, while Rosenbluth and Bobroff [4] used information obtained from amplitude modulation of the beat frequency signal. Cosijns et al. [9] developed an analytical model for periodic error taking into consideration the rotational misalignment of the input laser beam with respect to the PBS, non-orthogonality of the linearly polarized frequencies, ellipticity in the polarizations of the two frequencies, rotational misalignment of the mixing linear polarizer (LP), and the different transmission coefficients for the PBS. All other parameters are assumed to be ideal. This study uses the Cosijns et al. [9] model to compute sensitivity of the periodic error with respect to the contributing optical imperfections. The first and second order periodic errors are identified analytically and are summed to obtain the worst case periodic error. Sensitivity analysis is performed with respect to this sum.

3. SENSITIVITY ANALYSIS

Saltelli et al. [23] define sensitivity as: "The study of how the uncertainty in the output of a model

can be apportioned to different sources of uncertainty in model input." This study focuses on identifying which parameters in the heterodyne interferometry setup are most influential on periodic error by performing a sensitivity analysis. Given this information, efforts in aligning the interferometer may be optimized.

3.1 Global Sensitivity Analysis

Although local, or gradient-based, sensitivity analysis does provide a measure of the local response of the outputs obtained by varying each input parameter individually, it is ineffective for exploring the entire input parameters space in the case of uncertain inputs. The volume of the space explored is zero because the sensitivity is calculated only at one point with respect to one parameter, while all other parameters are kept constant. In order to obtain better estimates of variation of the outputs over the entire input parameter space, global sensitivity analysis is applied. Variance-based methods enable the computation of output sensitivities given uncertain inputs. These methods compute the output values at a number of points in the input parameter space and use information ascertained from a large number of model evaluations to calculate the sensitivity of the output with respect to each input. Global sensitivity measures provide an estimate of how much output variance would be reduced if a particular input parameter was fixed at a certain value. Some features of variance-based methods are [20]:

1. the sensitivity indices are model independent
2. they can capture the full range of input uncertainty
3. they can estimate the individual, as well as interactive, effects of model input on output
4. they can handle inputs which have some logical dependence on each other:

Various techniques have been suggested for sampling individual input parameter sets, including random sampling, Latin hypercube sampling, and quasi-random number generators. This study employs the Latin hypercube sampling method for generating the input parameter data set. The advantage of Latin hypercube sampling is that it provides improved coverage over the entire input parameter space. Subsequently, it avoids the formation of clusters in the input parameter

space which can occur when using random sampling techniques.

3.2 The Sobol' Method

Sobol' suggested a Monte Carlo method for computing global sensitivity indices of arbitrary groups of factors [26]. The individual effect of an input is defined as the reduction in output variance when the input is fixed at a certain value. The sensitivity index, S_i , is defined in terms of the unconditional variance of the output, $V(Y)$, and the variance in the output Y when the input parameter, X_i , is fixed, $V[E(Y|X_i)]$; see Eq.1.

$$S_i = \frac{V[E(Y|X_i)]}{V(Y)} \quad (1)$$

This index represents the primary (first order) effect of X_i on Y without taking into consideration interaction effects. These individual effect sensitivity indices identify which parameters most influence output variation and can be used in a factor prioritization setting.

The total effect sensitivity index takes into consideration the interactive effects of the various input parameters on output variance. The total effect sensitivity index, S_{Ti} , is expressed in terms of $V(Y)$ and the output variance $V[E(Y|X_{-i})]$, which is the variance computed when all parameters except X_i are fixed. See Eq. 2.

$$S_{Ti} = 1 - \frac{V[E(Y|X_{-i})]}{V(Y)} \quad (2)$$

The total effect sensitivity indices can be used in a factor fixing setting. If $S_{Ti} \approx 0$, then X_i can be fixed at any value within its input range without affecting the output variance.

3.2.1 Calculation of Sobol' sensitivity indices

A Monte Carlo approach is used to compute the Sobol' sensitivity indices, where larger sample sizes yield increased accuracy of the results. The step-by-step procedure adopted to calculate the sensitivity indices follows.

1. Define two $N \times k$ matrices, A and B , using a Latin hypercube sampling technique where N is the number of samples and k is the number of input parameters. The column of each matrix corresponds to an input parameter with values within its input

uncertainty range. Note that A and B are generated independently and are separate matrices.

$$A, B = \begin{bmatrix} x_1 & x_2 & \dots & x_{k-1} & x_k \\ x_1^2 & x_2^2 & \dots & x_{k-1}^2 & x_k^2 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ x_1^{N-1} & x_2^{N-1} & \dots & x_{k-1}^{N-1} & x_k^{N-1} \\ x_1^N & x_2^N & \dots & x_{k-1}^N & x_k^N \end{bmatrix} \quad (3)$$

2. Define a C_i matrix for each input parameter by replacing the i^{th} column ($i = 1$ to k) of the B matrix with the i^{th} column of the A matrix.

$$C_i = \begin{bmatrix} x_{1B} & x_{2B} & \dots & x_{iA} & \dots & x_{k-1B} & x_{kB} \\ x_{1B}^2 & x_{2B}^2 & \dots & x_{iA}^2 & \dots & x_{k-1B}^2 & x_{kB}^2 \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots & \vdots \\ x_{1B}^{N-1} & x_{2B}^{N-1} & \dots & x_{iA}^{N-1} & \dots & x_{k-1B}^{N-1} & x_{kB}^{N-1} \\ x_{1B}^N & x_{2B}^N & \dots & x_{iA}^N & \dots & x_{k-1B}^N & x_{kB}^N \end{bmatrix} \quad (4)$$

3. Compute the model output using input samples from the A , B , and C_i matrices; this generates the output vectors. Each row of the A , B , and C_i matrices forms a single input data point.

$$y_A = \begin{bmatrix} f(A) \\ f(A^2) \\ \vdots \\ f(A^{N-1}) \\ f(A^N) \end{bmatrix} \quad y_B = \begin{bmatrix} f(B) \\ f(B^2) \\ \vdots \\ f(B^{N-1}) \\ f(B^N) \end{bmatrix} \quad y_{C_i} = \begin{bmatrix} f(C_i) \\ f(C_i^2) \\ \vdots \\ f(C_i^{N-1}) \\ f(C_i^N) \end{bmatrix} \quad (5)$$

4. The individual effect sensitivity indices are:

$$S_i = \frac{\frac{1}{N} \sum_{j=1}^N y_A^j y_{C_i}^j - f_o^2}{\frac{1}{N} \sum_{j=1}^N (y_A^j)^2 - f_o^2}, \text{ where } f_o^2 = \left(\frac{1}{N} \sum_{j=1}^N y_A^j \right)^2 \quad (6)$$

5. The total effect sensitivity indices are:

$$S_{Ti} = \frac{\frac{1}{N} \sum_{j=1}^N y_B^j y_{C_i}^j - f_o^2}{\frac{1}{N} \sum_{j=1}^N (y_A^j)^2 - f_o^2} \quad (7)$$

3.2.2 Characteristics of Sobol' sensitivity indices

1. S_i is a measure of how much the output variance can be reduced by fixing X_i . This is independent of the interactive effects or the total effect sensitivity indices.
2. S_{Ti} is greater than S_i in the presence of interactive effects; it is equal to S_i when there are no interactive effects.
3. The difference between S_{Ti} and S_i is a measure of the interactive effects for a particular parameter.
4. If $S_{Ti} = 0$ (S_i is also equal to zero), this indicates that a particular parameter has no influence on the output and can be fixed at any value within its input uncertainty range.
5. The sum of all S_i is equal to 1 for models with no interactive effects (additive models) and is less than 1 for models with interactive effects (non-additive models). The difference $1 - \sum S_i$ is an indicator of how significant interactive effects are in the model.
6. The sum of all S_{Ti} should always be greater than 1 and is equal to 1 for additive models.

4. PREDICTING PERIODIC ERROR FROM INPUT UNCERTAINTY

Given the most important parameters in Cosijns et al. model (α , θ , and β_{err} identified using the sensitivity analysis), the expected value of periodic error for a given combination of setup uncertainties can be determined. A Monte Carlo simulation (MCS) is used to evaluate the expected periodic error for uncertain inputs. The expected value of the periodic error is considered to be the value below which 95% (2σ) of the periodic error values computed during the MCS lie. A sample size of 2000 is used to perform the MCS.

Expected periodic error is computed for a complete array of uncertainties in the non-orthogonality of the two frequencies, rotational misalignment of the PBS, and rotational misalignment of the mixing LP. The uncertainties in the ellipticities and transmission coefficients are kept constant due to their low sensitivity. Contour plots are plotted here for different values for uncertainty in the mixing polarizer orientation.

From the simulation data, a regression fit with higher-order terms was completed in order to obtain an expression for the expected value of periodic error, pe (the sum of first and second

order contributions). A satisfactory fit was obtained with the inclusion of cubic terms. The expression is of the form:

$$pe = b_0 + \sum_{p=1}^k b_p x_p + \sum_{p=1}^k \sum_{q=p}^k b_{pq} x_p x_q + \sum_{p=1}^k \sum_{q=p}^k \sum_{r=q}^k b_{pqr} x_p x_q x_r, \quad (8)$$

where the b terms are the regression coefficients, k is the number of variables (α , θ , and β_{err}), and x gives the uncertainties in α , θ , and β_{err} . This expression provides an estimate of the expected value of periodic error given uncertainties in the setup misalignments. The expression does not incorporate uncertainty in the beam ellipticities, $d\epsilon_1$ and $d\epsilon_2$, or transmission coefficients, ξ and χ ; their uncertainties are assumed to be constant.

5. RESULTS

5.1 Sobol' Sensitivity Indices

The Sobol' individual effect and total effect sensitivity indices are computed using the Monte Carlo approach described previously with a sample size of 1×10^6 . The input parameter uncertainty ranges used in the analysis are listed in Table 1 (normal distributions were assumed).

TABLE 1. Uncertainty ranges for input parameters.

Parameter	Uncertainty range (3σ)
α	5 deg
θ	5 deg
$d\epsilon_1$	1 deg
$d\epsilon_2$	1 deg
ξ	0.05
χ	0.05
β_{err}	1 deg

Table 2 shows the individual effect, total effect, and interactive effect sensitivity indices computed for first and second order periodic errors. As can be seen from the results, for the given input range, periodic order error is mainly dominated by β_{err} . However, the total sensitivity index for α and θ are also significant, indicating that their interactive effects with other parameters are important. The angular orientations α , θ , and β_{err} are the main interacting parameters. The beam ellipticities, $d\epsilon_1$ and $d\epsilon_2$, and the transmission coefficients, ξ

and χ , have little influence. Other simulations conducted with different input uncertainty values produced similar results.

TABLE 2. Sobol' sensitivity indices.

	Individual effect S_i	Total effect S_{Ti}	Interactive effect $S_{Ti} - S_i$
α	0.125	0.411	0.286
θ	0.034	0.304	0.270
$d\epsilon_1$	0.036	0.135	0.099
$d\epsilon_2$	0.038	0.135	0.097
ξ	0.002	0.013	0.011
χ	0.002	0.014	0.012
β_{err}	0.387	0.641	0.254

5.2 Periodic Error Prediction

Expected values of periodic error are computed for an array of input uncertainties ($\alpha = 0$ to 5 deg, $\theta = 0$ to 5 deg, and $\beta_{err} = 0$ to 1 deg). Contour plots are then plotted in the α - β_{err} plane for different values of θ uncertainty. From these plots, the expected value of periodic error can be identified for a given combination of input parameter uncertainties. The uncertainty in the ellipticities is fixed at 1 deg; the transmission coefficient uncertainties are 0.05. The periodic error is evaluated in nm. Figures 2 and 3 show contour plots for two different uncertainties in θ (5 deg and 2 deg, respectively).

Using these figures, a regression fit (with higher order terms) to the expected periodic error, pe , yields Eq. 9, where insignificant terms have been eliminated. Note that the α , θ , and β_{err} terms are the 3σ normally-distributed uncertainties. Equation 9 can be used to estimate the expected periodic error given uncertainties in α , θ , and β_{err} for any single pass heterodyne interferometer setup.

$$pe = 0.4115 + 0.2807\beta_{err}^2 + 0.0011\alpha^2\theta + 0.0009\alpha\theta^2 - 0.0048\alpha\theta - 0.0788\beta_{err} + 0.0182\alpha\beta_{err} + 0.0005\alpha^3 - 0.0092\alpha\beta_{err}^2 \quad (9)$$

6. CONCLUSIONS

The Sobol' global sensitivity indices method was used to evaluate individual and total effect sensitivity indices. The sensitivity indices obtained from this analysis suggested periodic error depends mainly on the rotational misalignments α , θ , and β_{err} . Only β_{err} showed a significant individual effect; however, α and θ interact with each other as well as with β_{err} and significantly affect periodic error. This suggests that, in order to restrict periodic error to a low

value, the rotational alignment of the laser beams with the PBS and the rotational alignment of the mixing polarizer must be accurate. Also, a laser source with orthogonal (linearly polarized) frequencies must be selected. The contour plots as well as the expression for expected value of periodic error can be a useful tool in predicting periodic error when the uncertainties in the optical setup misalignments are known.

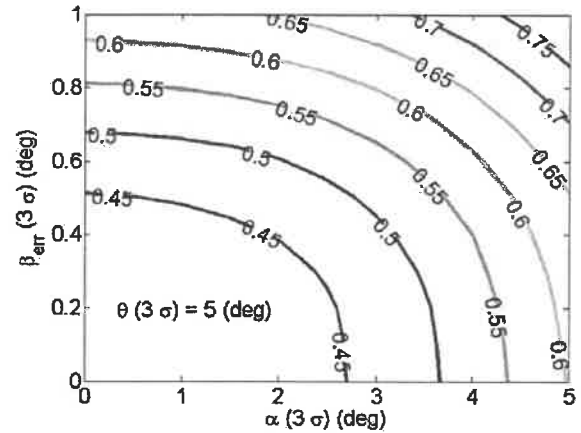


FIGURE 2. Contour plot for expected periodic error ($\theta = 5$ deg).

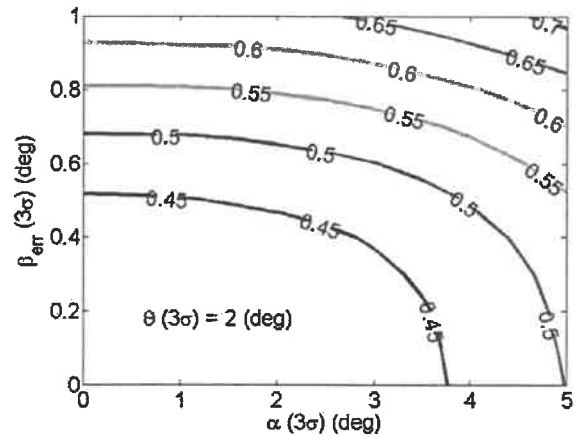


FIGURE 3. Contour plot for expected periodic error ($\theta = 2$ deg).

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WAVELENGTH SCANNING INTERFEROMETER FOR STRUCTURED SURFACES

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INTRODUCTION

Structured surfaces are a fundamental building block for many applied sciences and high-tech products, across fields as diverse as energy production and bio-engineering. For example, surfaces used in photonics, optics in high-power laser-energy systems, interfaces in fluid-dynamics (energy-efficient jet engines), extended life human joint implants and MEMS/NEMS devices [1]. A simple example of such a surface is structured optical film that perform a number of functions including collimation, focusing, diffusion, re-direction, brightness enhancement and out-coupling.

The method which is used most often for the assessment of thin film quality in many optical manufacturing processes is to examine the ability of the finished thin film surface to perform its designed function. This method can lead to excessive cost and high scrap rates as it is essentially a post-process technique. Recently, progress has been made to measure and characterize such surfaces using a replica technique for indirect measurement in a metrology lab [2]. However, if an optimized manufacture is to be achieved, it is desirable for the molds as well as the films to be measured during the manufacturing process.

In the past few years, an optical chip and a near common-path optical fibre interferometer have been developed by the authors [3-4]. The optical principles for these interferometers are based on measuring the phase shift of light reflected from the surface using a combination of Wavelength/Frequency-Division-Multiplexing (WDM/FDM) techniques, which provide phase-to-depth and wavelength-to-field detection. These have proved to have the potential for on-line measuring at the nano scale for both stochastic and structured surfaces, but are limited in scale to measure complex geometric surface structure sizes ranging from nanometres up to hundreds of micrometers.

In this paper a fundamentally improved WDM/FDM technique, for micro structured surface measurement is presented. The proposed wavelength scanning method is an attempt to form a new kind of on-line surface measurement system that is fast, robust and suitable for implementation in CNC machine centers and production lines. It is expected that this system will measure structured surfaces that can currently only be measured in standard laboratories by electro-mechanical scanning based white-light interferometry.

MEASUREMENT PRINCIPLE

The optical principle is based on measuring the phase shift of a reflected optical signal using the advanced WDM/FDM derived from an acousto-optic tunable filter (AOTF). The wavelength scanning surface measurement system is illustrated in Figure 1. It is composed of two interferometers that share a common optical path. The measurement interferometer, illuminated by a white light source, is used to acquire areal data from the sample in real time. The reference interferometer, illuminated by a stabilized laser diode, is used to monitor and compensate the environmental noise, e.g. temperature drift, mechanical vibration and air turbulence. As the two interferometers suffer similar environmental noise, the measurement interferometer will be capable of measuring surface information once the reference interferometer is "locked" into compensation mode.

The light beams from the white light source and the laser diode are coupled by a dichroic mirror. The dichroic mirror is highly reflective in the infrared and highly transmissive in the visible light range. Therefore, the power of the two light sources can be fully utilized and any infrared components of the white light source are blocked. After passing through the beam splitter BS1, the light beam is expanded by the beam expander. The system adopts a Michelson configuration in which BS2 acts as a beam splitter. Light reflected by the sample and the

reference mirror are combined by BS2 to generate an interferogram. An acousto-optic tunable filter (AOTF) is used to select the light output from the interferometer so that an interferogram of only certain wavelength components of the white light source are detected by the CCD. The selected light wavelength is determined by:

$$\lambda = \Delta n \alpha \frac{v_a}{f_a} \quad (1)$$

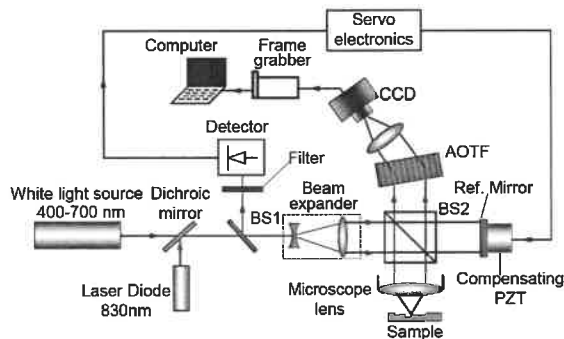


FIGURE 1. Schematic diagram of the wavelength scanning interferometry system

where Δn is the birefringence of the crystal used as the diffraction material, α is a complex parameter depending on the design of the AOTF, v_a and f_a are the velocity and frequency of the acoustic wave respectively. The wavelength of the light that is selected by this diffraction can therefore be varied simply by changing the driving frequency f_a . As a result, different wavelengths of light will pass through the AOTF in sequence so that a series of interferograms at different wavelengths will be detected by the CCD. The absolute optical path difference can be calculated in real time by analyzing the interferograms captured by the CCD.

IMPROVED MEASUREMENT SYSTEM

An optimized experimental configuration is illustrated in Figure 2. In this system, the AOTF is removed from the imaging system and placed in the light source path. The light source is separated from the interferometers, transfer to the interferometers takes place via a fiber patch cable. The laser diode is replaced by a near infrared SLED as the reference interferometer light source, to further reduce the interference signal noise. The Michelson interferometer is replaced by a Linnik one to reduce the dispersive errors induced by the unbalanced arm of the Michelson interferometer. By

separating the light source and the AOTF from the interferometers, not only have the size and weight of the interferometers been greatly reduced, but the thermal influence from the light source has also been eliminated.

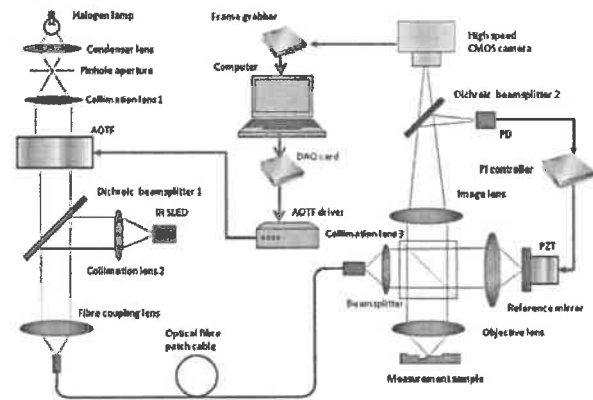


FIGURE 2. Schematic diagram of the optimized wavelength scanning interferometry system

A key feature of this experimental setup is the placement of the acousto-optic tunable filter (AOTF). It is placed after the white light source to select a specific wavelength for the interferometer, thus producing an interferogram at the CCD sourced only by that specific wavelength. The selected light wavelength is determined by equation (1).

It is well known that surface measurement in the workshop/manufacturing environment has been difficult to achieve using interferometric methods because they are so sensitive to vibrations; in particular, axial (vertical) vibration [10]. In addition, measurement noise can also be induced by temperature drift and air turbulence. In this experimental study, the reference interferometer is illuminated by a SLED and together with a servo feed-back electronic unit, it effectively compensates for environmental noise. Light output from the SLED is combined with the measurement light and travels almost the same optical path as the measurement interferometer. The interference signal of the reference interferometer is acquired by a photodiode after being separated off by dichroic beamsplitter 2. As a result of a shared optical path it is envisioned that if the noise occurring in the reference interferometer is monitored and compensated for, the measurement interferometer will 'see' no noise during measurement. The reference interferometer is

locked at around quadrature to maximize sensitivity to environmental disturbances. The PZTs used has a resolution of up to 0.05 nm and a frequency response of 35 kHz (P-249.10, Physik Instrumente). As such, the noise compensation can be very quick and accurate provided the load is light. This technique has been effectively tested and proved in our previous research [11-12].

The experimental system uses a high speed CCD camera which captures 300 frames during the wavelength scanning process; each pixel of the CCD camera collects 300 intensity values. The intensity values of just one pixel can be processed at a time to obtain the information of one point of the sample surface if a single core CPU is used. The computing structure required has to be repeated 337334 times in a sequential execution to analyse the structure of a surface captured by the (672 x 502) pixel array of the CCD camera.

In order to overcome the data processing difficulty, a graphics processing unit (GPU) GeForce GTX 280 with 240 cores has been used to dynamically accelerate the computing process. The huge parallel programming capability of the GPU has accelerated the floating point calculation throughput by a factor of twenty from the dual core CPUs used in the experiment. The sequential execution program using Matlab code with dual core CPU has been restructured with CUDA C programming to achieve the data parallelism. The computation time has been reduced from 31.4 seconds to under one second.

EXPERIMENTAL RESULTS

The method described in the previous section was used to measure standard height specimens and different types of structured surfaces; two examples are presented here. In these experimental studies, the radio frequency applied to the AOTF (Model LSGDN-1, SIPAT Co.) was scanned from 80MHz to 110MHz in steps of 10 kHz, corresponding to a wavelength interval of 0.48nm. This range of radio frequency provides a range of scanning wavelengths from 680.8nm to 529.4nm. During the wavelength scanning process, 300 interferograms were recorded by the high speed CCD camera (Model OK-AM1131, JoinHope Image Tech. Ltd.) at a frame rate of 100 frames/s. Figure 3(a) shows the intensity distribution recorded by one of the CCD pixels (100,100). Figure 3(b) shows the

corresponding retrieved phase of this intensity distribution. It can be seen from Figure 3(b) that this result suffers from discontinuities, where the values are in the range from $-\pi$ to π . These discontinuities have been corrected by adding 2π at the discontinuous points to obtain a continuous phase distribution as shown in Figure 3(c). By using the continuous phase distribution, the sample step height of this pixel can be calculated.

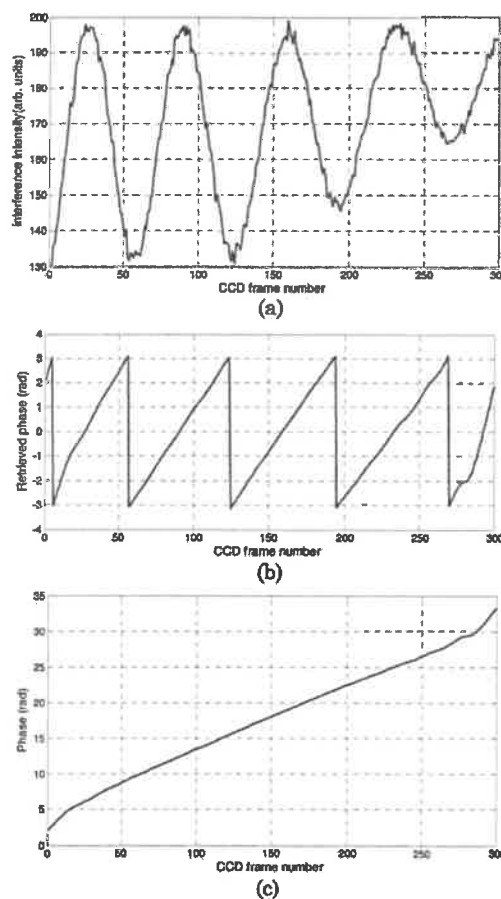


FIGURE 3. (a) Intensity distribution for 300 interferograms captured by a CCD pixel (100,100) (b) Retrieved phase discontinuous distribution (c) Phase continuity distribution.

A standard step height specimen with a calibrated step of $2.970\mu\text{m}$, provided by National Physical Laboratory (NPL), UK was used as a measurement sample. This specimen has been processed according to the above proposed measurement procedure and an areal surface view obtained as shown in Figure 4. The measured average step height is $2.971\mu\text{m}$ with a measurement error of 1nm.

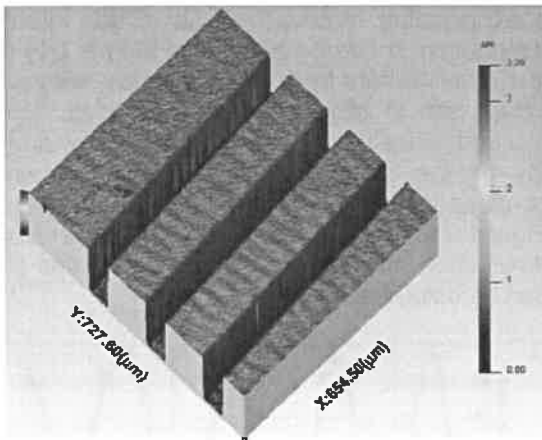


FIGURE 4. Measurement results of a $2.97\mu\text{m}$ standard step

The second measurement example was to investigate the effectiveness of the instrument's vibration compensation as follows:

- (1) A semiconductor daughterboard sample was measured without inducing mechanical disturbance. The measured surface step height is $4.7564\mu\text{m}$ (Figure 5).
- (2) A 40 Hz and 400 nm peak-to-peak sinusoidal mechanical disturbance using a PZT was applied to the reference mirror. During the disturbance, the measured surface step height is $11.711\mu\text{m}$ (Figure 6). The surface roughness signal is extremely distorted.
- (3) When the vibration compensation is switched on, a reduction in the disturbance movement of the fringe pattern is clearly observed. The measurement of the sample at this stage was carried out. The data were retrieved as the original measurement and illustrates that the compensation vibration can be used to overcome environmental disturbance. The measured step height is $4.7429\mu\text{m}$ (Figure 7).

The difference between the two measured step height values is 13.5 nm. The measurement results are shown in Figures 5, 6 and 7 respectively. The observed disturbance attenuation between the parts (2) and (3) of the experiment was 12.2 dB, according to the reference interferometer signal output, which is in good agreement with the measured standard sample error.

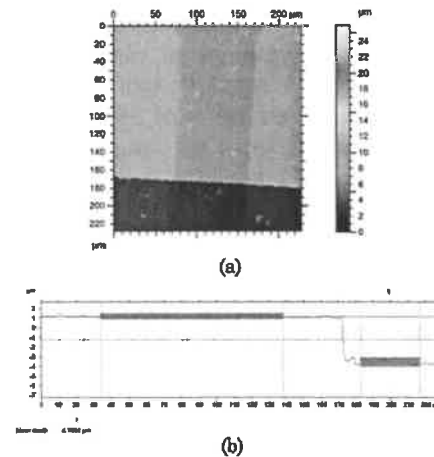


Figure 5. Measurement results of a semiconductor daughterboard sample without an induced mechanical disturbance: (a) measured surface and (b) cross-sectional profile.

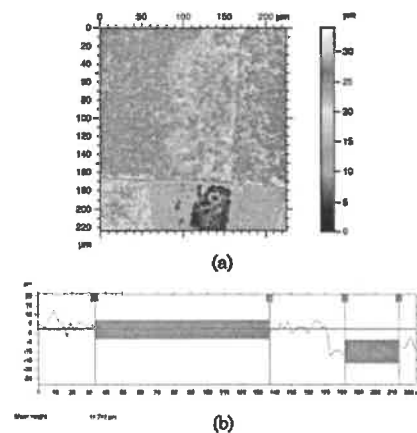


Figure 6. Measurement results of a semiconductor daughterboard sample with a sinusoidal mechanical disturbance of 40 Hz

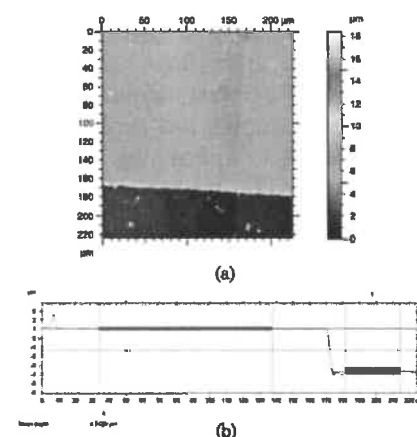


Figure 7. Measurement results of a semiconductor daughterboard sample with vibration compensation.

DISCUSSION

We have presented an approach for on-line measurement technology for structured surface measurement based on Wavelength/Frequency-Division-Multiplexing (WDM/FDM) and graphics processing unit (GPU) techniques. A surface measurement technique with active control of environmental noise has been discussed. Nanometer accuracy surface measurement results have been obtained for micrometre step height samples. There is also no need for optical path scanning as found in conventional white-light vertical scanning interferometry. A SLED with 850nm wavelength shares the same optical path as the measurement interferometer to introduce vibration compensation feedback loop. Disturbance has been reduced by 12.2 dB at a 40Hz vibration frequency. The follow-on research will adopt a higher speed CMOS detector and optimizes the GPU parallelization techniques to further speed up and simplify this measurement system.

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A NON-CONTACT SURFACE MEASUREMENT SYSTEM FOR COMPLEX OPTICAL GEOMETRIES

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1. INTRODUCTION

Current techniques for the surface figure metrology of complex shapes are limited. Optipro Systems is developing a non-contact measurement system called UltraSurf. The goal is to characterize concave and convex surfaces of aspheric and freeform shapes up to 200 millimeters (mm) in diameter with precision and without the limitations associated with other measurement methods. Measuring is done by using state of the art motion control components and a non-contact probe. In this work, we review the recent development of the UltraSurf system and the methods of surface measurement. In addition, future work and experimentations are discussed.

2. METHODOLOGY

The UltraSurf traverses a non-contact probe over the part under test while staying normal to the surface. A description of the part's shape is required and is supplied to the UltraSurf before measurement occurs. Some manual alignment of the part is required for the UltraSurf to maintain the probe's depth of field. Symmetry in the part can be exploited during the alignment and measurement procedures for efficiency.

2.1 UltraSurf Mechanical Specifications

The UltraSurf has five axes of motion available to measure complex optical shapes (Fig.1). There are two rotary, and three linear axes. All of the axes are precision air bearings. The two rotary axes are brushless direct current motors while the three linear axes are linear induction motors. The smoothness of air bearing travel eliminates errors typically associated with mechanical systems, such as bearing frequency. Each axis reads its position from a high-resolution scale. The X, Y, and C axes move the part under test, while the Z and B axes move the non-contact probe. The specifications for UltraSurf's motion capabilities are listed in Table 1. Air pressure is monitored and precisely controlled to prevent errors data due to pressure fluctuation. The UltraSurf is located in a temperature controlled metrology lab.

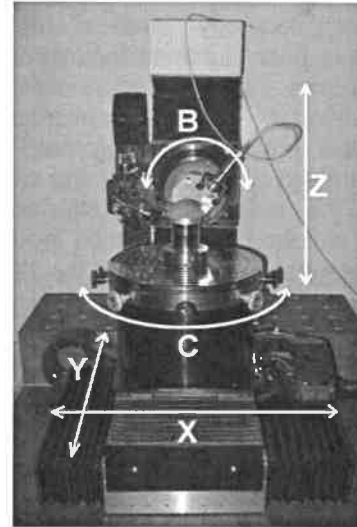


FIGURE 1. Photograph of UltraSurf with labeled axes of motion. Probe is attached to B-Axis.

TABLE 1. Specifications for the axes of motion.

Axis	X,Y,Z	B	C
Travel	200 mm	360°	360°
Resolution	5 nm	0.018"	0.009"
Accuracy	25 nm	0.09"	0.045"

2.2 Non-Contact Probes

Multiple non-contact probes have been installed and tested on the UltraSurf. Optipro currently measures with two types of probes, but the UltraSurf is not limited only to these. Although each probe shares the ability to read a distance from a reference point they have unique qualities. The first probe uses low-coherence interferometry (LCI) [1] with a safe, near infrared laser. It is able to read the thickness of multiple surfaces at a single point. The LCI probe can measure distance when coupled with an internal reference plate. The second probe uses confocal chromatic sensing (CCS) with white light to measure distance at a single point [2]. It is more accurate than the first probe, but can only measure one surface at a time [3]. Both probes have proved capable of measuring many different optical materials that have rough or fine surface texture.

2.3 Output Data

The exported data from the UltraSurf is a cloud of points. The cloud is fit to the nominal surface and form is removed, resulting in an error map of the surface relative to the nominal. The fitting procedure removes any misalignment of the part during the measurement, therefore meticulous manual alignment is not required. Visualization of the data is done through false color plots using triangle based interpolation for data gridding (Fig.2).

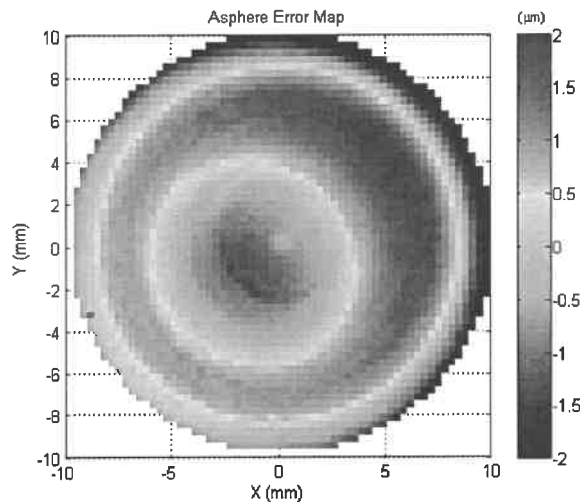


FIGURE 2. False color map of an asphere's deviation from nominal. Color scale is in micrometers. Asphere scanned with CCS probe.

3. CURRENT WORK

OptiPro is testing the different non-contact probes on known optical surfaces to qualify the methodology. Spheres and flats have been successfully measured and compared against standard interferometry. Large windows have been the focus of current UltraSurf testing. Several spherical domes of various materials have been mapped on the UltraSurf, each in the realm of 165 mm in diameter.

3.1 Glass Spherical Dome

A glass dome was recently measured where the surfaces were polished, but exhibit large errors in form (Fig.3a, Fig.3b). Both surfaces were measured simultaneously with the LCI probe. The thickness map of a dome is produced along with the surface error plots (Fig.3c).

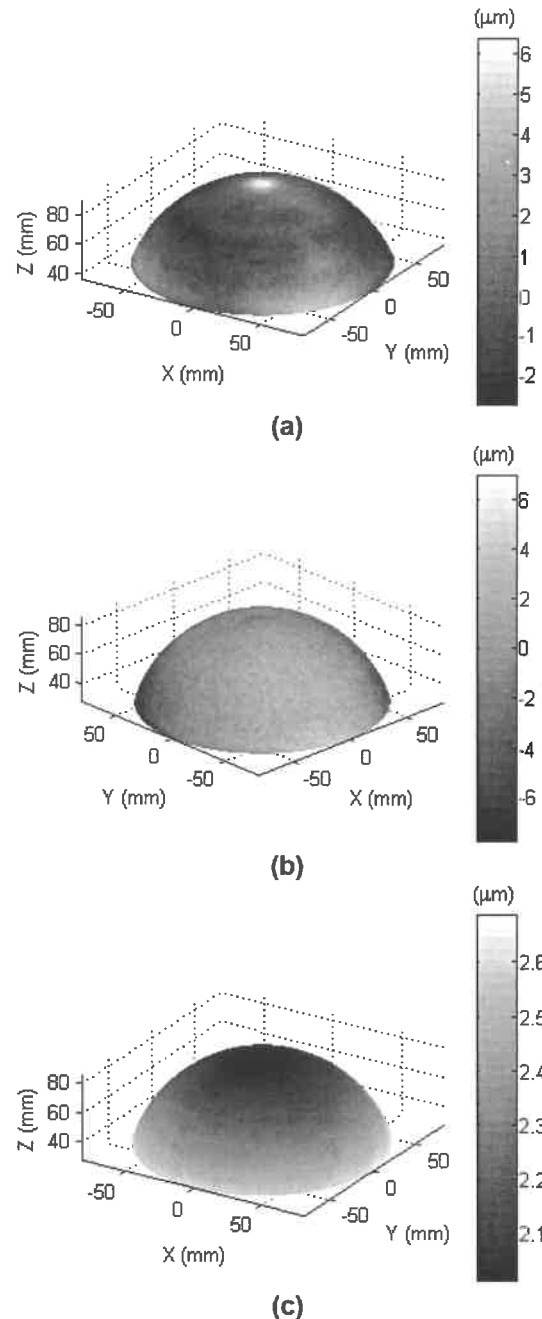


FIGURE 3. False color error maps of a large glass dome on UltraSurf with the LCI probe. Fig.3a shows the convex outside surface, Fig.3b shows the concave inside surface, color scale is in micrometers. Fig.3c shows the false color thickness map of a large glass dome, color scale is in millimeters. The dome has a center thickness smaller than the edge.

Generally, the largest component of thickness variation is a curve mismatch driven by center thickness (Fig.4). A complete understanding of the thickness can allow for better process control. Wedge is easily calculated from the full thickness map. The value will essentially be an edge thickness difference (ETD). This method is not as sensitive to surface irregularities like a standard ETD measurement.

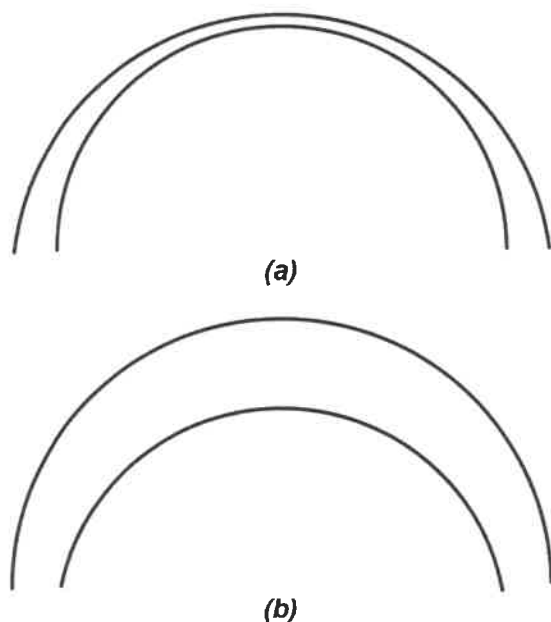


FIGURE 4. Curve mismatch types, Fig. 5a: thin center thickness, thick edge, Fig. 5b: thick center thickness, thin edge

3.2 Glass Ogive

The inside and outside surfaces of a large polished glass ogive have been mapped using the LCI probe (Fig.5). The surface measurement was performed by following the convex outside of the ogive and measuring through the material. The data was cropped near the center producing a flat tip in the data. There is color information at the tip, but this is an artifact of superimposing the error map over the surface of the ogive. The inside and outside surfaces of the ogive exhibit signatures related the grinding process. Both surfaces show significant errors in form. The dome was quickly polished in order to “grey out” the surface. OptiPro will use the data as feedback into the UltraForm computer controlled deterministic polishing platform, with the goal of correcting the measured form error. UltraSurf is currently the only system with the capability to measure the ogive shape in a rough or polished condition and produce a full 3-D model with deviation from nominal.

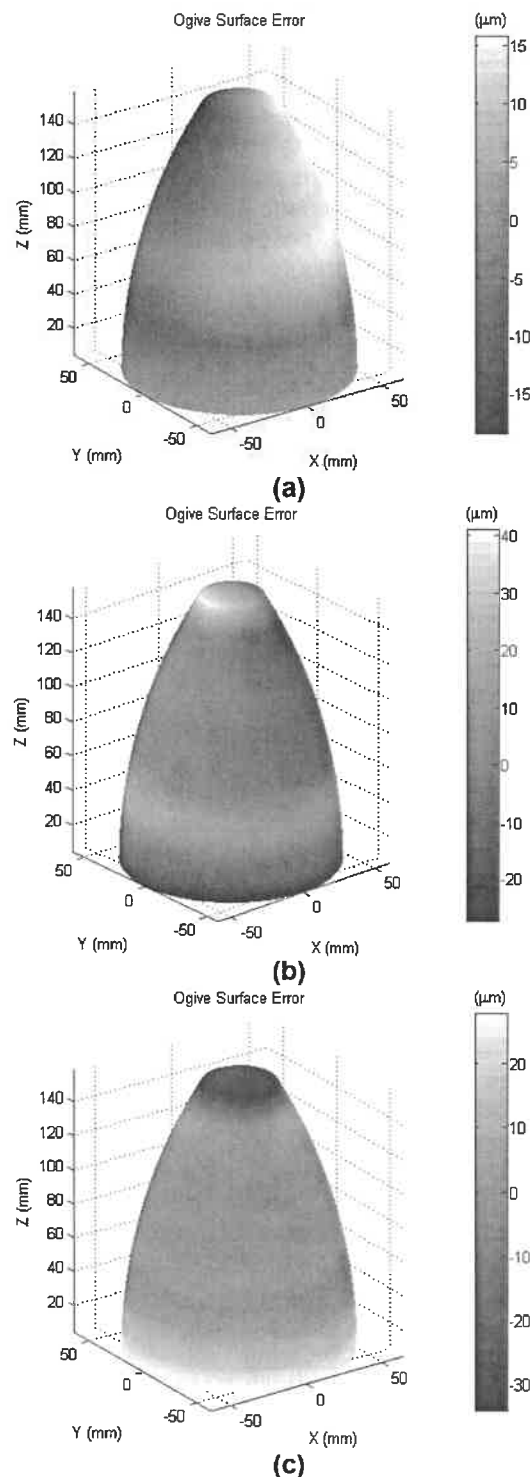


FIGURE 5. False color error maps of a large glass ogive on UltraSurf with the LCI probe Fig.6a shows the convex outside surface, Fig.6b shows the concave inside surface. Fig.6c shows the false color thickness variation from mean of a large glass dome, color scale is in micrometers.

3.3 Toroid

The top surface of a toroid was measured on the UltraSurf (Fig.6). The toroid requires all five axes of motion to keep the probe normal to the surface. The previous shapes had rotational symmetry that did not require all five axes. The toroid is about 76 mm in diameter and has about 6 mm of sag height change from the center to the edge. Five-axis measurement paths for the toroid were generated through the use of surface normal vectors, which are perpendicular to the surface [4]. Surface normal vectors can be found using analytical or numerical means.

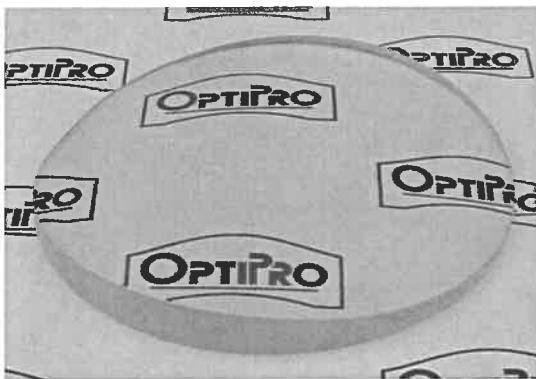


FIGURE 6. Polished toroid measured on the UltraSurf. $R1=175$ mm, $R2=100$ mm.

The surface error plot for the toroid (Fig. 7) shows very pronounced streaks in the direction of the long radius of curvature. These marks come from using a sub-aperture polishing technique, but without using a deterministic polishing algorithm to create the polishing path.

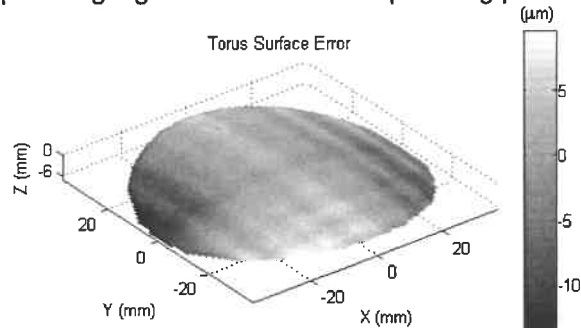


FIGURE 7. Polished toroid surface error, measured on the UltraSurf the LCI probe. Color scale is in micrometer.

3.4 Aspheric Toroid

An aspheric toroid (Fig.8) was also measured using the same techniques as the standard toroid. The aspheric toroid has polynomial terms

to influence the shape like a standard asphere. Inputting the formula for this shape into the UltraSurf allowed it to easily able measure the surface deviation (Fig.9). Because this shape is a window we can also measure the thickness and second surface also long as the two surfaces are parallel enough.

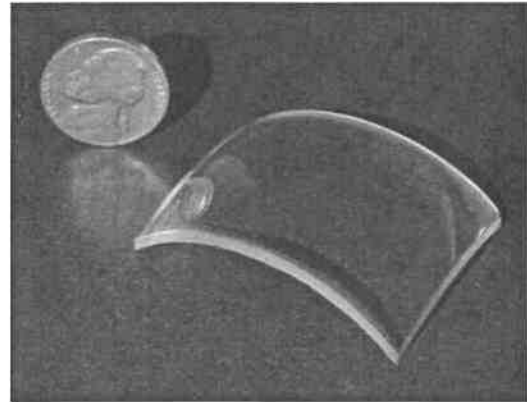


FIGURE 8. Polished toroid measured on the UltraSurf. $R1=75$ mm, $R2=34$ mm.

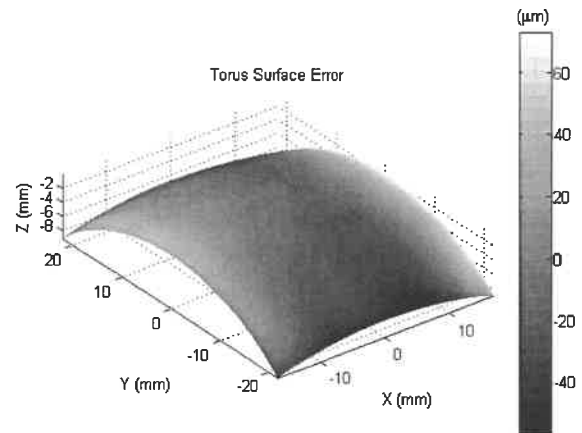


FIGURE 9. Polished aspheric toroid surface error, measured on the UltraSurf the LCI probe. Convex side. Color scale is in micrometers.

4. FUTURE WORK

OptiPro plans to measure several different toroidal surface shapes with five-axis methods on the UltraSurf. Methods exist for measuring toroids with relatively flat radii of curvature on Interferometricly. Therefore, comparison can be made with the UltraSurf. OptiPro is continuing to test shapes can be verified via secondary methods as a way to prove out the system.

If metrologists do not have the exact prescription for the part under test, or wanted to save time on

alignment of complicated surfaces like freeforms, then they could measure with a multipoint non-contact probe. Multipoint probes can collect data from many points over a small area, allowing the current surface normal vector to be calculated. Once the current surface normal is known, the computer could “blindly” step to the next area to be measured by predictive algorithms. These non-contact probes are commercially available and under research. ASE Optics and STIL are developing multipoint probes. The probes are utilizing the low-coherence interferometry and confocal chromatic sensing techniques respectively [1, 2, 5]. OptiPro will be testing blind contour techniques with the UltraSurf

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CHALLENGES AND SOME SOLUTIONS FOR THE MEASUREMENT OF ASPHERIC AND FREEFORM SURFACES

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INTRODUCTION

The characterization of aspheric and free-form surfaces belongs to one of the most challenging tasks in the interferometric measurement of surfaces. The benefits of employing such surfaces have been known since long time. Because almost every basic shape is allowed, the main difficulty lies in implementing measurement configurations that allow accommodating the required slope and aspherical departures for a wide spectrum of surfaces. Classical problems like high fringe density, vignetting and the presence of retrace errors [1]-[2] require the use of clever arrangements between interferometer and test object as well as custom made algorithms for the removal of interferometer induced aberrations. Although several alternatives have been proposed [3]-[4], none of them truly succeeds in fulfilling the requirements concerning flexibility, accuracy and measurement time.

In this work we present a non-conventional solution based on an interferometer performing in a non-null test configuration making use of an array of test beams. Each test beam contains a defined amount of tilt that locally matches the slope of the test object, thus reducing the fringe density and avoiding vignetting at the same time. No repositioning of the test object is required to cover the whole test surface, hence reducing the overall measurement time and increasing the accuracy of the method. Since no kind of symmetry or particular geometry is necessary from the test surface, the measurement system is especially attractive to be employed in the characterization of free-form elements.

TILTED-WAVE INTERFEROMETER

The set-up of the interferometer can be seen in Fig. 1. Here a laser source *L* after filtering and collimation by the spatial filter *SF* impinges on a microlens array followed by a pinhole array to generate altogether a point source array (PSA). After collimation by lens *L*₂ we obtain a set of

plane waves with different amounts of tilt that make possible the compensation of surface gradients with similar slope deviations to these tilts. A transmission sphere *TS* adds a certain amount of power to the tilted waves to compensate the basic conical shape of the surface.

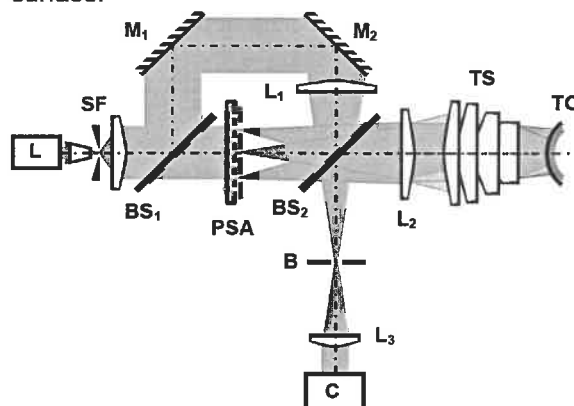


FIGURE 1. Tilted-wave interferometer set-up. *L*: laser source; *SF*: spatial filter; *M*₁ and *M*₂: fold mirrors; *PSA*: point source-array; *BS*₁ and *BS*₂: beam splitters; *L*₁: reference beam focusing lens; *L*₂: collimation lens; *TS*: transmission sphere; *TO*: test object; *B*: interferometer aperture; *L*₃: imaging lens; *C*: camera.

The test beam is then reflected at the test surface *TO* and after imaging onto the camera by *L*₃ interferes with the reference beam from the upper branch of the interferometer. The interferometer aperture *B* with a square shape limits the fringe density on the detector. The particular selection of this shape for the aperture will become clear in the next sections.

Figure 2 shows the outgoing tilted spherical waves from the transmission sphere converging to the Cat's eye position. The additional test beams allow an extension of the test angular spectrum. These allow accommodating a large range of test objects with strong slope variations without the need of modifying the interferometer setup or repositioning the test object as in other available techniques.

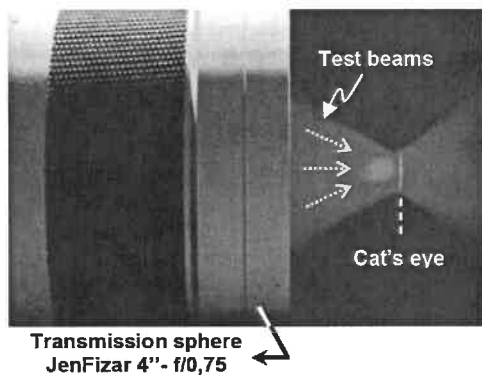


FIGURE 2. Tilted test beams showing the extended test angular spectrum of the interferometer (Experimental).

The basic working principle of the interferometer is illustrated in Fig. 3 where a test object TO (plane mirror) with a large tilt α is measured. If an on axis source S is used, the test beam will be blocked at the interferometer aperture B and no interference results on the camera. In order to correct this situation we observe that if we modify the incidence angle of the test beam to the test surface by an amount of twice its tilt (2α), after reflection on the surface the test beam follows the path of the axial source S, thus ideally reducing the fringe density to zero. If we now consider a test object with a basic conical shape, the gradient α becomes a local property of the surface, therefore requiring more than one source (an array) to cover the whole range of slopes.

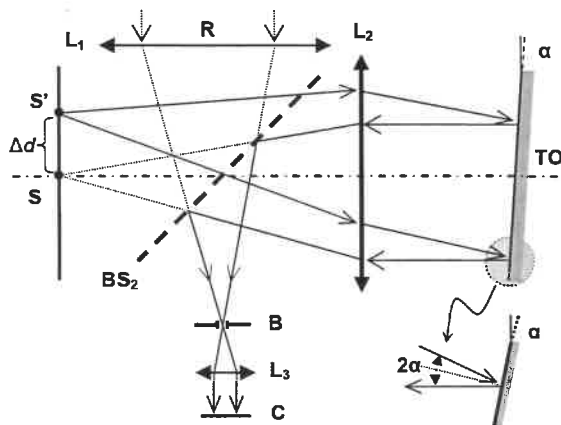


FIGURE 3. Working principle of the tilted-wave interferometer.

Figure 4 (a) shows a typical interferogram as seen on the camera for a rotationally symmetric surface when all the sources of the array are active. The long coherence length of the laser

source makes possible for neighboring point sources of the array to interfere between them. In Fig. 4 (b) we can see this unwanted effect between contiguous sources when the reference beam is blocked. To avoid this overlap leading to multiple beam interference, an activation sequence where only every fourth source of the array (every second column and row) is active is used. The resulting interferograms are shown in Fig. 5 along with their corresponding source activation pattern on the bottom left. This is accomplished by a selection mask in front of the array that blocks the unwanted sources. It is important to note that the positioning accuracy of the mask is not critical since the size of the source pinholes is in the order of $30\text{ }\mu\text{m}$ and the separation between contiguous sources is almost 2 mm .

In this way, the entire test surface is covered in four measurements, requiring a measurement time in the order of 45 seconds for the complete surface.

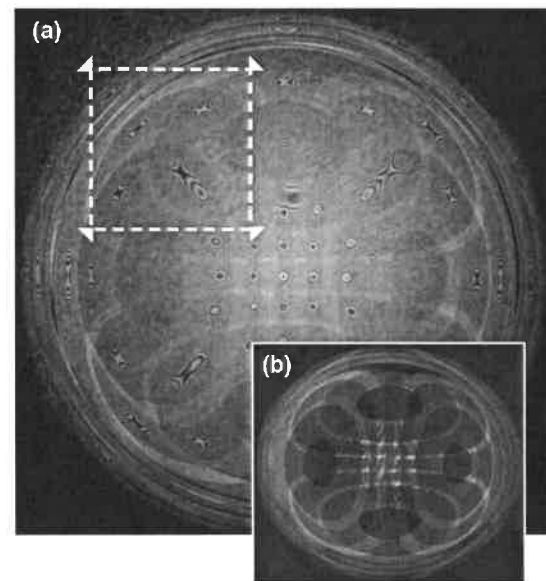


FIGURE 4. Interferogram for a rotationally symmetric test surface. (a) Interferogram with all the sources of the array activated. (b) Interference between contiguous sources of the array can be observed when the reference beam is blocked.

For each one of the sources in the array the interferometer aperture B (see Fig. 1) limits the maximal slope reaching the camera so that the fringe density in each one of the sub-apertures in Fig. 5 remains below the Nyquist rate.

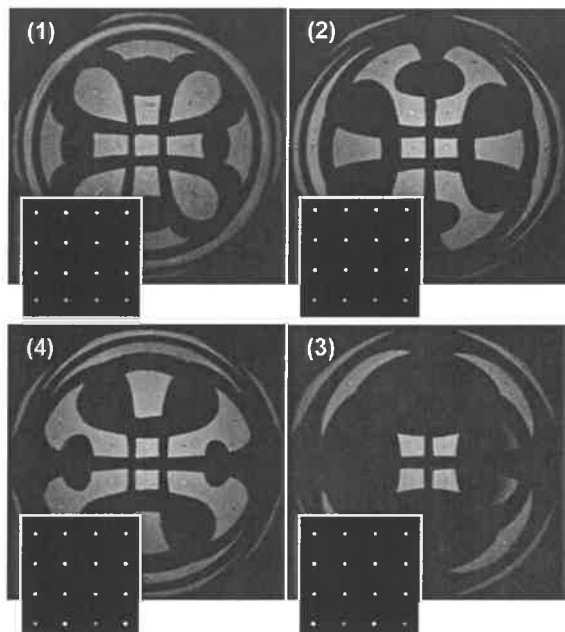


FIGURE 5. Interferograms with partial array activation. Every second row and second column is activated for each one of the four frames (a)-(d). On the bottom left the active source pattern for the current interferogram is shown (white: active source; gray: blocked).

From the previous four measurements we can then calculate the figure error of the surface [5], as shown in Fig. 6.

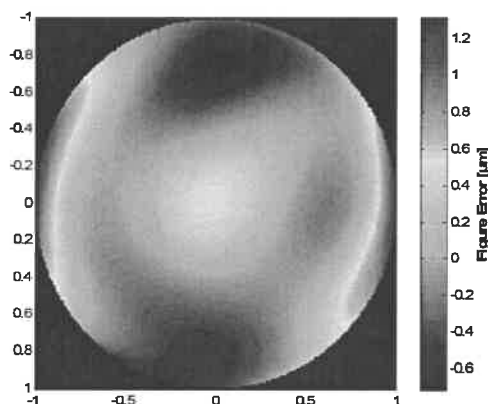


FIGURE 6. Figure error of the test surface calculated from the four measured phase maps.

INTERFEROMETER CHARACTERIZATION

Since the compensation of the surface gradients by a given source of the array is only perfect at one point in its corresponding sub-aperture, the fringe density increases in its neighborhood due to the slope mismatch between test beam and

test surface. Figure 7 shows the highlighted section of the full aperture interferogram in Fig. 4 (a).

As discussed in the introduction, for techniques that work violating the null test condition, usually a large contribution from the interferometer itself (retrace errors) to the measured aberrations has to be considered along with the figure error of the test object. In the present interferometer arrangement, where an array of sources is being used, the aberrations for each one of the sources have to be accurately characterized in order to correctly extract the figure error of the test object.

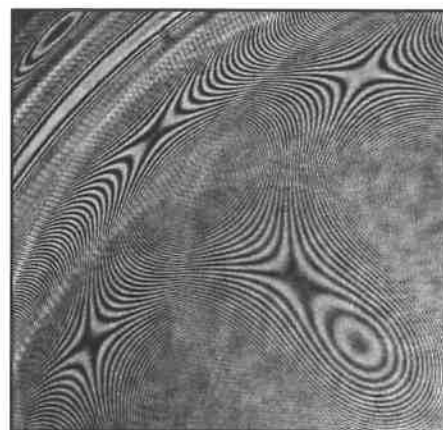


FIGURE 7. High fringe density interferograms in each sub-aperture. The presence of fringes violating the null test condition requires an accurate characterization of the interferometer set-up.

The problem becomes then the identification of small aberrations due to the test object (figure error of the surface) in the presence of aberrations several orders of magnitude larger caused by the different optical paths (on the way to- and from the test surface) followed by the test beams through the interferometer. Since these system aberrations are dependent on the shape of the test surface, they must be calculated every time that we consider a new test surface prescription or modify the measurement set-up.

Several methods have been proposed so far for the characterization of an interferometer working under a non-null (or partial null) arrangement. The vast majority are based on successive steps of raytracing of the interferometer and optimization of the degrees of freedom for the critical components in the system. This optimization process becomes extremely complex and time consuming even if a reduced

number of elements are considered. For the characterization of the tilted-wave interferometer this method becomes unfeasible because of the large number of sources and free parameters. Since only the overall effect of the paths in the interferometer is desired a different approach based on the use of characteristic functions was implemented [5]-[6]. Applying the formalism of the point characteristic functions we can characterize, with the help of some reference planes conveniently located in the system, the wavefronts propagating to- and from the test surface after reflection on its surface. Figure 8 shows the location of these two planes, E_Q and E_P , in the test space of the interferometer. Both planes have associated two characteristic functions $Q(M, N, X, Y)$ and $P(m, n, x, y)$ that describe the optical paths between source array and test space for the first function, and for the second one between test space and camera. The coordinates (M, N) and (m, n) represent the position of a source in the source array PSA and a pixel on the camera C respectively.

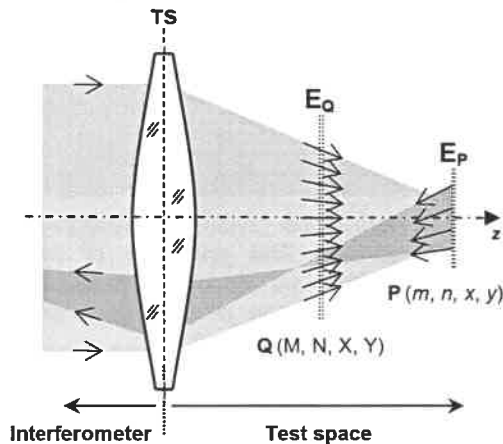


FIGURE 8. Interferometer characterization. The reference planes E_Q and E_P allow describing the propagation of the test beams through the interferometer.

Due to the complexity of usual interferometer configurations, only special cases allow a closed exact expression for both characteristics Q and P . Instead an analytical description based on a polynomial (Zernike) fit is taken for each one of the functions.

Now, this model has to be corrected to account for the real interferometer configuration (component deviations from their nominal design, erroneous positioning in the interferometer, and many more) since Q and P are initially calculated with the nominal data of

the system. This correction (calibration) is done through a series of measurements with a reference sphere at several positions in the test space of the interferometer [6].

MEASUREMENT OF ASPHERES AND FREEFORM SURFACES

Given a test surface prescription it is possible to represent for each surface element the corresponding slope capture range for the interferometer. That is the slope of the test beam that can be captured by the interferometer after reflection on the test surface.

Figure 9 shows the case where the test beam is the one for the on-axis (central) source of the array. If a beam, after reflection on the surface, remains inside the slope capture area (full arrow); it will reach the camera with a slope such that the fringe density of the interferogram can be resolved by the camera. Otherwise, if the beam lies outside this area (dotted arrow), it will be blocked at the interferometer stop; meaning that we can not measure this section of the test surface with this particular source of the array. The measurement areas are then given by a central zone and a ring shaped interferogram.

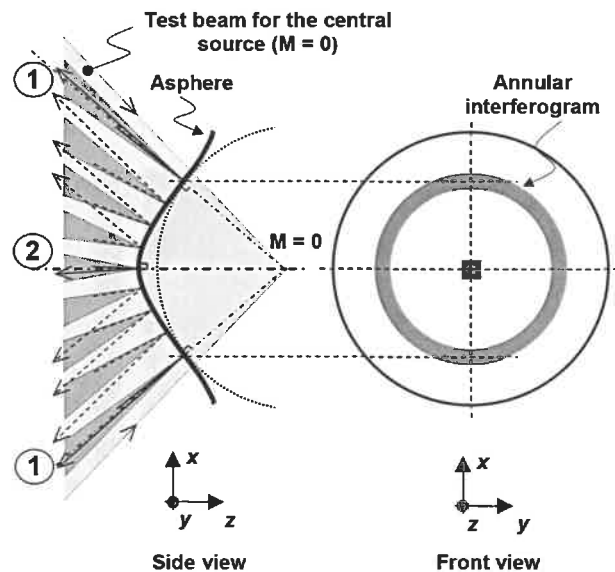


FIGURE 9. Interferometer slope capture. On-axis source.

The question now is how the other areas of the test surface are reached. Figure 10 depicts again the previous measurement configuration but now, the test beam starts from an off-axis source of the array. Due to the shift in the angular spectrum of the source, a different

section of the test surface falls now into the slope capture of the interferometer. In this way, for each source of the array defined sections of the test surface are selected through the interferometer aperture such that the fringe density does not become too high for the camera.

Clearly the gradient step between test waves has to be designed such that every element of the test surface falls into the slope capture of the interferometer for at least one source (there could be more than one).

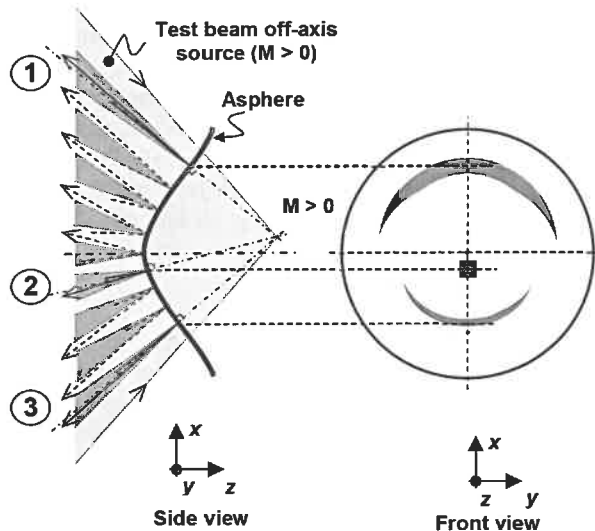


FIGURE 10. Interferometer slope capture. Off-axis source.

The previous example was taken for a rotationally symmetric surface but since no kind of symmetry of the test surface is required the same reasoning applies.

SUMMARY

The interferometric measurement of surfaces with geometries other than planar or spherical introduces serious difficulties if great flexibility and accuracy are desired. In particular the measurement of freeform surfaces remains one of the most challenging problems in the interferometric characterization of surfaces. The tilted-wave interferometer introduces an alternative to the available methods offering great flexibility and accuracy.

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QUESTIONS

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INCREASED LATERAL RESOLUTION OF SPHERES AND ASPHERES THROUGH SUBAPERTURE STITCHING INTERFEROMETRY

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ABSTRACT

Optical surface specifications that prescribe the allowable error as a function of spatial frequency, such as limits on the PSD or local slope, are becoming more common. It is often important to characterize errors on an optical surface that range in size from the wavelength of light all the way up to the size of the optic. A range of instruments is required to accurately measure surface errors over this full spectrum and a typical optics shop has gaps in coverage. High-resolution subaperture stitching is one way to extend an instrument's spatial frequency measurement capability and close a problematic gap in this coverage. An explanation of how stitching increases resolution will be discussed and examples will be given that show the benefits of stitching over full-aperture metrology.

INTRODUCTION

The Fizeau interferometer has become a standard tool in optics shops for evaluating the quality of an optical surface with high accuracy and precision. It does, however, have strict limitations when dealing with large physical apertures, large numerical apertures, or aspherical surfaces. Its spatial resolution is also generally insufficient for measuring small surface features known as mid-spatial frequencies.

Subaperture stitching is a well-known technique for overcoming many of the limitations of Fizeau interferometry by extending its effective aperture and dynamic range [1,2]. Stitching has been routinely applied to extend the spatial coverage of plano interferometers. However, it has been much more difficult to apply stitching techniques to spherical and aspherical interferometric testing because of the complications with alignment, motion control, and subaperture data processing.

In 2003, QED Technologies introduced the Subaperture Stitching Interferometer (SSI[®]) [3], the first commercially-available interferometer specifically designed to perform high-accuracy

subaperture stitching of spherical and flat surfaces. The SSI combines a precision six-axis motion platform, a commercial 4" or 6" aperture Fizeau interferometer, and a specially-developed software package that automates measurement design, subaperture data acquisition, and the mathematical reconstruction of a full-aperture phase map. Additionally, the stitching algorithm compensates several types of errors introduced by the interferometer and stage mechanics, including positioning errors, viewing system distortion, the system reference wave error, etc [4].

Stitching can also increase the amount of testable aspheric departure. This is made possible by measuring locally-nulled subapertures with a higher magnification than what would be used for full coverage of the part. The resolution of what would otherwise have been higher density interference fringes is thereby enabled. In 2006, QED introduced the Subaperture Stitching Interferometer for Aspheres (SSI-A[®]) [5] allowing the measurement of aspheres with up to approximately 200 waves of departure from the best-fit sphere.

Most recently, the stitching concept has been extended to even higher-departure aspheres with up to 1000 waves of departure on the Aspheric Stitching Interferometer (ASI[®]) [6]. The ASI, introduced in 2009, uses variable optical null (VON[™]) technology – a configurable set of auxiliary optics between the test optic and reference surface that nearly matches the local aspheric shape at each subaperture location.

This paper explores the benefits of using magnification to measure fine spatial frequency features on a part by using the capabilities of QED's stitching algorithms. Typical phase shifting interferometers have CCD detectors with resolution of 1000 x 1000 pixels or less. Image sensors with greater than 1 million pixels are readily available, but the interferometer's Instrument Transfer Function (ITF) generally limits the effectiveness of simply adding pixels to

the detector to gain resolution. On the other hand, optical magnification and stitching can be used to give a real increase in spatial resolution over that achieved by full-aperture tests. The increased spatial resolution obtained through stitching is demonstrated through a comparison of the power-spectral density (PSD) plots for a variety of surfaces. Full aperture measurements of both spherical and aspherical surfaces are presented using standard techniques and high-resolution subaperture stitching interferometry. The benefits and applications of high-resolution stitched measurements are also discussed.

RESOLUTION LIMITS OF CONVENTIONAL FULL APERTURE INTERFEROMETRY

When measuring an optic using a Fizeau interferometer, the minimum resolvable feature size is equal to the interferometer's field of view (which depends on the transmission element, the test optic's radius of curvature, and the interferometer zoom setting) divided by one-half the number of illuminated pixels – this is the Nyquist limit.

In addition to the Nyquist limit, the Instrument Transfer Function (ITF) also limits the size of the minimum resolvable feature. The apparent amplitude of features begins to gradually decline at some frequency, effectively setting the practical resolution limit. This limit is often 2-10x worse than what is specified by the Nyquist limit alone [7].

In conventional interferometry, there is generally a requirement that the entire part surface be seen with a single measurement, and therefore the interferometer's field of view must be larger than the size of the test optic, limiting the number of pixels that can be used for a full-aperture test.

Thus, for large optics or surfaces whose mid-spatial features must be accurately quantified, the resolution of a conventional interferometer is often insufficient.

Stitching interferometry solves both of these problems by eliminating the requirement that the interferometer's field of view be larger than the optic's diameter (increasing the number of pixels that can be used) and by allowing the use of slower transmission spheres with improved ITFs.

Power Spectral Density (PSD)

Evaluating the PSD is useful for quantifying the figure error distribution as a function of spatial frequency. The ITF can also be clearly observed and analyzed by using PSD plots. As discussed in other papers [8], some processing of the data is required prior to performing a PSD analysis in order to mitigate the effects of spectral leakage. Applying a weighting function (such as a Hamming window) or using polynomial fitting are some ways to minimize the effects of spectral leakage when evaluating the PSD. For the data presented in this paper, a set of Zernike polynomials has also been removed from every measurement to reduce spectral leakage and to highlight the high-spatial frequency information. Stitched measurements with low-order figure error included have been presented in many other papers [9,10].

HIGH RESOLUTION, SUBAPERTURE STITCHING

Recent advances in QED's stitching algorithms have enabled high-resolution stitching, so that in many cases, it is possible to generate a stitched result at the same pixel scale as the subaperture measurements. While subaperture stitching has always given improved resolution over full aperture tests due to the increased ITF of slower transmission spheres, the result often must be down-sampled because of computer processing and memory limitations.

Because QED's stitching algorithm stitches subapertures simultaneously, and not sequentially, a significant amount of memory would be necessary to stitch together tens of subapertures at full resolution. However, the full subaperture resolution is not required for stitching to resolve the mismatch between subapertures.

HIGH RESOLUTION SPHERE MEASUREMENTS

A series of measurements was acquired on a 31.75 mm Silicon Nitride ball over an aperture of 21 mm with three transmission spheres of varying f-numbers: an f/0.75, f/1.5, and f/3.3. In theory, the measurement using the f/0.75 transmission sphere, imaged onto 600 pixels, should allow us to measure features as small as 70 microns. However, when comparing this measurement to stitched measurements with the f/1.5 and f/3.3 transmission spheres, it becomes clear that many of the high-spatial frequency features have been blurred. The PSD plot also

gives a quantitative assessment of what we can qualitatively see in the phase maps: the f/3.3 transmission sphere measures significantly more high-spatial frequency content than the f/0.75 transmission sphere. The measured figure error also increases as the contribution from higher frequency features is included in the measurement.

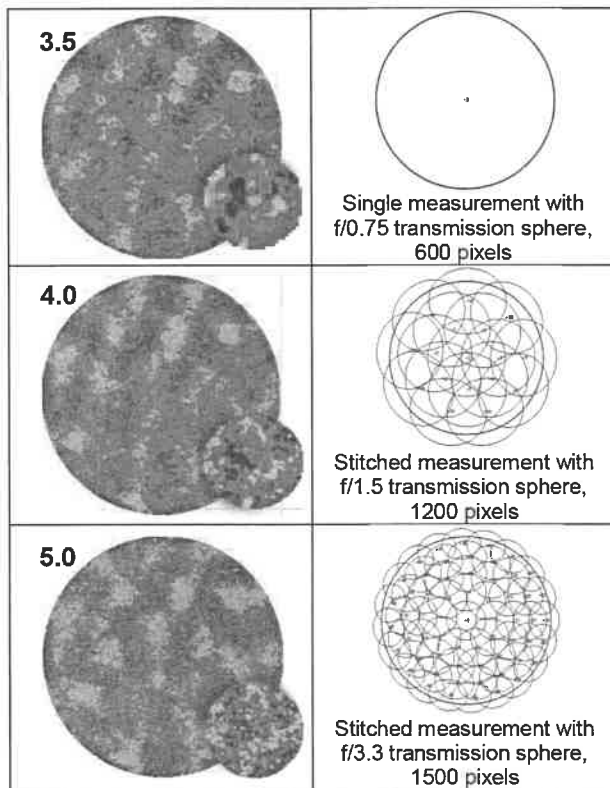


FIGURE 1. Stitched measurement and lattice of subapertures for three surface measurements; the rms error of the phase map, in nanometers, is displayed to the upper left; the central 1 mm region of the phase map is displayed to the lower right.

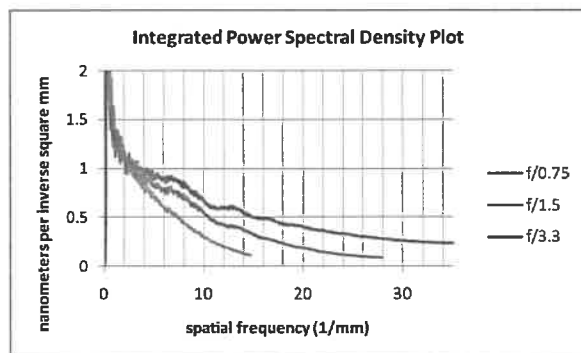


FIGURE 2. PSD plots of the three measurements displayed in FIGURE 1.

The effect of the ITF is clearly displayed in Figure 2. For low spatial frequencies, below $\sim 2 \text{ mm}^{-1}$, the three PSD plots agree quite well. At a spatial frequency of $3\text{--}4 \text{ mm}^{-1}$, the PSD plot for the f/0.75 begins to decline rapidly because of the ITF, and although being $1/4 - 1/5$ of the Nyquist limit, this is the effective resolution limit for this measurement configuration. The effective resolution limit for the f/1.5 is a little more than twice as large as that of the f/0.75, at approximately 10 mm^{-1} .

The results from this test clearly show that stitching can be very effective in increasing the lateral resolution of a measurement. However it is clear that the pixel scale alone does not define the resolution limit, and more careful analysis is required to determine what the practical resolution limit is. However, as a general rule of thumb, and consistent with the results shown, an interferometer's effective resolution is $\sim 5\times$ worse than that specified by the Nyquist limit.

Fidelity of the stitching process

As a sanity-check, we must compare a single subaperture measurement to its corresponding region in the full-aperture stitched measurement, to ensure that the effect shown above is not simply a side-effect of stitching. Two measurements are given below in figure 3: the subaperture measurement taken in the center of the part and the corresponding region in the full-aperture measurement (approximately the central 5 mm). In order to reduce the error in overlapping regions of a stitched measurement, inline calibration methods were developed to automatically calculate and remove errors in the reference wavefront [4]. Those errors have been removed as part of the stitching process and were therefore also subtracted from the single subaperture measurement as a separate post-processing step. The phase maps and PSD plots in figure 3 and figure 4 agree extremely well and do not show any unintended side effects of stitching (e.g. there are no stitching artifacts or blurring of features from mis-aligned overlapping subapertures).

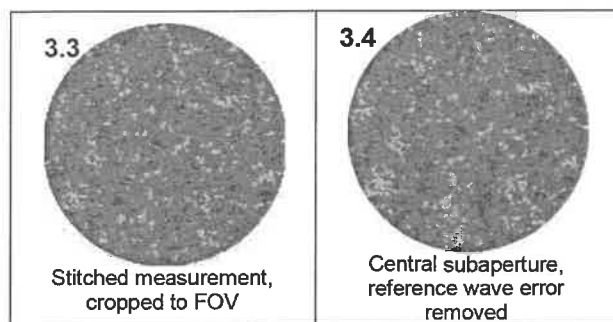


FIGURE 3. Single subaperture and corresponding section of stitched measurement; the rms error of the phase map, in nanometers, is displayed to the upper left

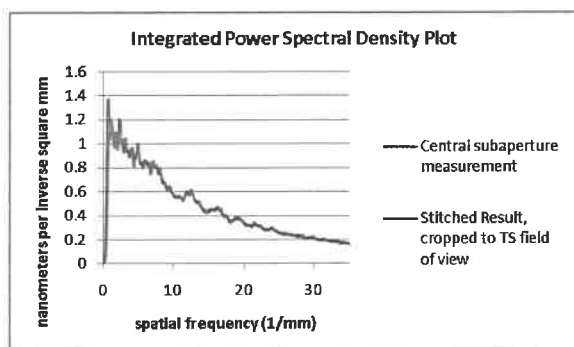


FIGURE 4. PSD plots of the measurements displayed in figure 3.

HIGH-RESOLUTION ASPHERE MEASUREMENTS

While conventional spherical polishing often results in smooth surfaces that are free of mid-spatial frequency content, most aspheric generating and polishing processes utilize subaperture tools that improve overall accuracy and cycle time, but are more susceptible to leaving mid-spatial features. Because of this, there is often a specification on aspheric prints limiting the local surface slope or mid-spatial frequency content on the part surface. In order to properly evaluate an aspheric surface against these specifications, the metrology tool that is used must be able to accurately measure the spatial frequencies of interest. QED has developed several products that can be used for this purpose: the MFA-400, the SSI(-A), and the ASI. The MFA-400's principal purpose is to evaluate mid-spatial frequency content; it stitches local regions of an aspheric surface using transmission spheres much slower than what would be used to cover a part's full aperture [11]. The SSI(-A) and ASI products provide less resolution than the MFA-400, but

have the advantage of providing a full-aperture phase map. This often means that the low- and mid-frequency errors can be captured with a single measurement. Additionally, if the amplitude and size of mid-spatial frequency features are not constant everywhere on the part, a full-aperture measurement will give the most representative result.

Asphere measured with stitching and a full-aperture CGH test

An asphere with a diameter of 48 mm, vertex radius of curvature of 158 mm, and 75 microns of aspheric departure was measured in two configurations. First, a full-aperture measurement was taken using a Computer Generated Hologram and a 4" f/3.3 transmission sphere on a 6" interferometer with a 1000 x 1000 pixel detector. Using the same interferometer, an ASI stitched measurement was acquired using a 6" f/5.3 transmission sphere. The slower transmission sphere used in the stitched measurement increases the number of pixels across the aperture by a factor of 3 from ~565 to ~1700. The results of the measurements and the PSD plots are shown in figure 5 and figure 6.

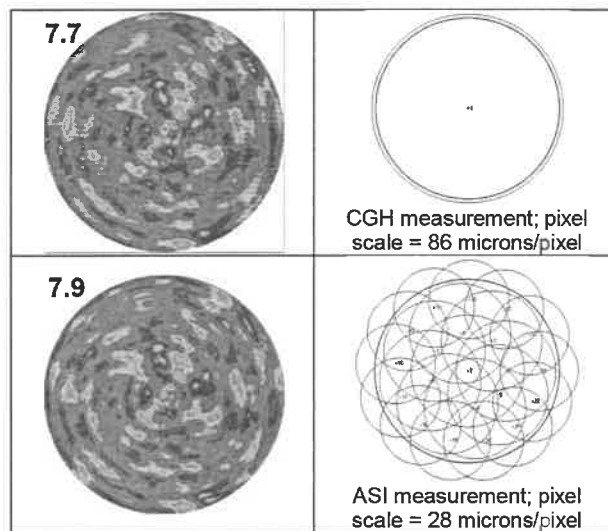


FIGURE 5. CGH and ASI stitched asphere measurements; the rms error of the phase map, in nanometers, is displayed to the upper left

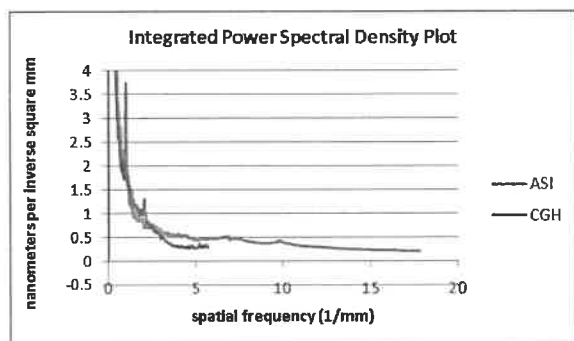


FIGURE 6. PSD plots of the measurements displayed in figure 5.

If we zoom in on the plot and only show spatial frequencies up to 6 mm^{-1} , we see that the two PSD plots begin to diverge at around 3 mm^{-1} . This is the approximate practical spatial frequency cutoff for the CGH measurement.

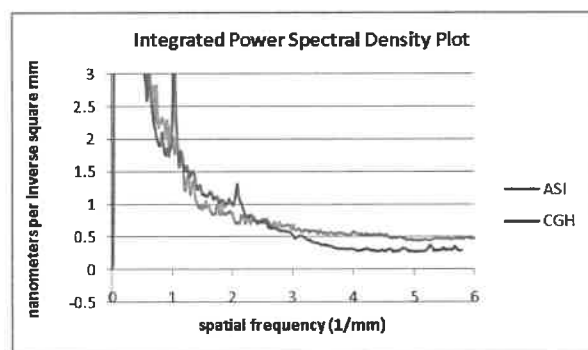


FIGURE 7. PSD plots for spatial frequencies up to 6 mm^{-1}

The resolution benefit from stitching is clearer when examining the surface figure error over a reduced aperture, as shown in figure 8. Over the central 15 mm, the CGH measurement shows some serious flaws: a “hot spot” in the center, which has resulted in dropout, and ghost fringes in the lower left quadrant. Note also the two large spikes in the CGH PSD plot corresponding to spatial periods of 0.5 and 1 mm (the horizontal line artifacts from the CGH test that are visible in the full aperture measurement). The measurement artifacts in the CGH test setup essentially render the CGH measurement unsuitable for an accurate mid-spatial frequency analysis, even for frequencies below the ITF cutoff frequency.

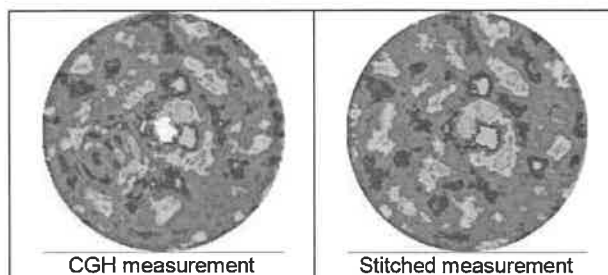


FIGURE 8. CGH and ASI stitched asphere measurements, cropped to 15 mm

In order to determine what the ITF cutoff frequency is for the ASI-stitched measurement of this asphere, a measurement with even higher spatial resolution was taken. A 1" f/14 transmission sphere was used with a 4" $\rightarrow$ 1" beam reducing telescope to measure the central subaperture of this asphere. The PSD plots were compared over an 8 mm aperture and are shown below in figure 9. The cutoff frequency for the 6" f/5.3 appears to be near 6 mm^{-1} , where the two plots begin to diverge. Therefore, the high-resolution stitched measurement from the ASI could be used to accurately evaluate the mid-spatial frequency errors in this part up to 6 mm^{-1} , twice what the CGH measurement is capable of.

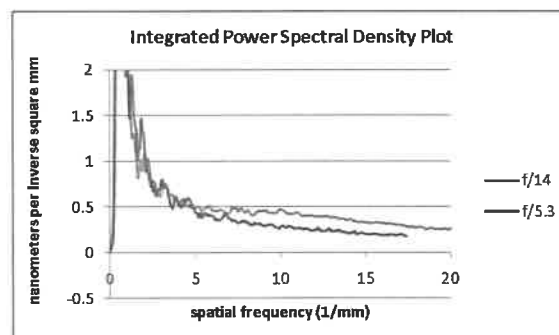


FIGURE 9. PSD plots for f/5.3 and f/14 transmission spheres

CONCLUSION

Full-aperture interferometric measurements often have insufficient resolution to measure mid-spatial frequency features of interest, especially when null optics such as CGHs are involved. High-resolution, subaperture stitching can be used to measure smaller features and thereby give wider coverage of PSD characterization than with a conventional full aperture test. A stitched measurement of an aspheric surface was shown to have significantly higher lateral resolution than a full-aperture test using a CGH.

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COMPACT DYNAMIC INTERFEROMETER FOR ON-MACHINE MEASUREMENT

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We present a compact, vibration insensitive interferometer design that is well suited for measuring optics while mounted in-situ on polishing equipment. The system employs a single frame phase sensor that permits acquisition in tens of microseconds to mitigate the effects of vibration or relative motion with the test part. The theory of operation is presented along with experimental test results, which characterize repeatability and precision under static and high-vibration conditions.

The vibration frequency response of the interferometer is assessed. In addition, Theoretical and measured instrument spatial resolution (instrument transfer function) and retrace error are compared. We also present preliminary measurements made with a prototype system mounted in a commercial polishing machine.

ON-MACHINE METROLOGY FOR ASPHERIC OPTICS TESTING

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INTRODUCTION

Recent needs for the production of both spherical and aspherical optical surfaces place demands on the manufacturing techniques of polishing and metrology. However, there are several commercial optical polishing processes that can perform very-deterministic material removal once an accurate surface error map has been produced; it is the provision of this surface error map that is often difficult and time consuming.

Part safety is also demanded and a great risk usually occurs in transferring the optic between polishing and metrology stages.

To this end, we have found it advantageous to measure surfaces in-situ on the polishing machine. On-machine measurement can be used to eliminate the need to frequently move the surface under test between the polishing and metrology apparatus, cutting risk and the amount of time spent clocking parts in on the interferometry and on the polishing spindle.

One problem that arises in this methodology is that often the shop floor is a noisy environment ill-suited to traditional optical form interferometry. However, these problems can be overcome using today's vibration insensitive interferometry.

One application for such on-machine metrology is for the manufacture of telescope mirrors. We have previously used in-situ metrology for polishing process development using a fixed optical test tower above a Zeeko Intelligent Robotic Polishing (IRP) machine for telescope mirror-like optics [1]. We have now extended that work and designed a metrology system able to test a wide range of part radii, and able to be fitted with computer generated holograms (CGH) for aspheric testing. A CAD representation of the system is shown in figure 1.

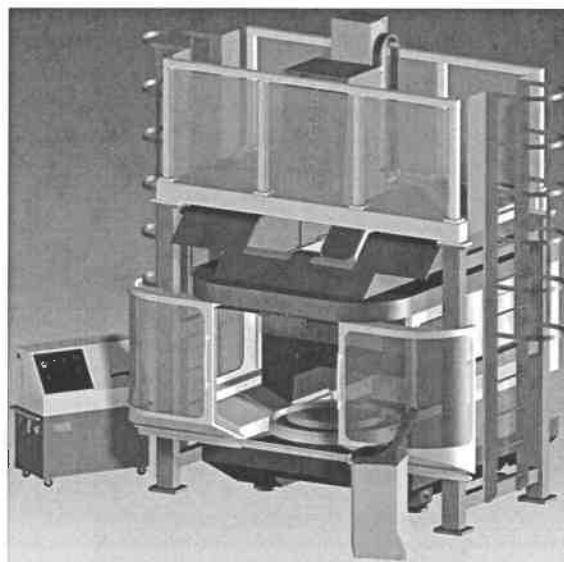


FIGURE 1. CAD representation of the On-Machine metrology system. IRP 1000 polishing machine, optical test tower and interferometer mounted on 5-axis CNC stage..

MULTI-AXIS INTERFEROMETER STAGE

The first requirement is for a flexible system that is able to position the interferometer at the appropriate points relative to the centers of curvature of the optics under consideration, where the optic under test is mounted on the polishing machines rotary table (Zeeko c-axis). There is also the requirement for fine focus and tip/tilt adjustment, and also a requirement to cope with significant wedge in the part by way of lateral translation. With these in mind, and experience gained on a prototype interferometry rig using translations and tilt, we designed a Computer Numeric Control (CNC) 5-axis stage to position the interferometer with axis specifications as shown in table 1. The travel range on the Z-axis was set by a requirement to

measure surfaces with base radii of curvature of between 1200 mm and 2400 mm.

TABLE 1. Specifications of the 5-axis CNC interferometer positioning stage.

Axis	Range	Resolution
X	± 100 mm	1 μ m
Y	± 100 mm	1 μ m
Z	-1440 mm	1 μ m
A	± 1 deg	0.135 arc sec
B	± 1 deg	0.135 arc sec

A prototype mechanical stage was built and tested using a commercial Fizeau interferometer before the full CNC system was built up. Figure 2 shows a CAD model of the 5-axis stage and the Fizeau interferometer. An additional hinge, normally locked, allows the interferometer cage to tip 90 degrees to allow mounting of the interferometer atop the test tower.

Control of the stage is via a handheld controller connected to the main CNC controller with range, axis, jog and manual control of the axes. The stage is primarily designed for testing rotationally symmetric spheres and aspheres, but can be arranged to accommodate non-rotationally symmetric parts depending on the exact surface specification.

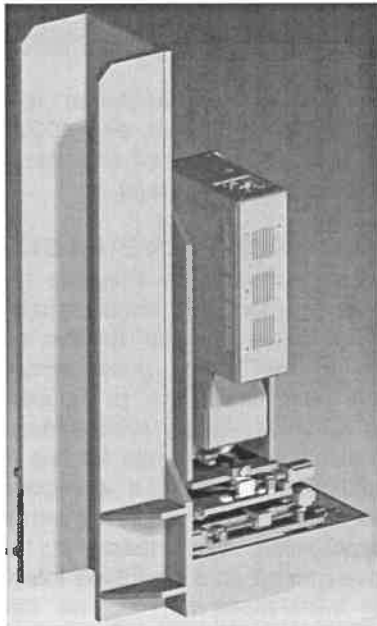


FIGURE 2. CAD representation of the 5-axis interferometer stage.

CGH Element Holder

A Diffraction International 150 mm CGH positioner is mounted to the interferometer cage on sliding rails with coarse and fine-micrometer adjustment to facilitate the alignment of the CGH with the interferometer. This way, once the CGH has been adjusted to the interferometer, the two move together as a rigid unit as shown in figure 3.



FIGURE 3. Detail of the Fizeau interferometer and CGH mounting arrangement. Fizeau shown with plano element in use.

OPTICAL TEST TOWER

The test tower comprises a stiff steel structure with an upper platform and access ladder to enable the user to adjust and change the interferometer transmission element. Computer and alignment camera displays are duplicated atop the test tower allowing the lone adjustment of the test elements.

We have previously used separate test tower and access platforms to perform such on-machine metrology to avoid vibration problems caused by personnel on the tower, but with the 5-axis CNC system controlling the interferometer, once the CGH and interferometer have been adjusted, the tower is vacated and all further adjustments are made from the ground. The use of a 4D FizCam 3000 interferometer further ensures that we do not need to have vibration isolated platforms.

OPTICAL TESTING INTERFEROMETER

To ensure maximum flexibility, a 6" Fizeau interferometer was chosen such that 4" or 6" transmission elements could be used. A 4D Technology FizCam 3000 unit is mated to the 5-axis stage where we derive the benefit of the vibration handling capability of the 4D system. The unit is used in dynamic phase-shifting mode at 633 nm.

COMPLETE SYSTEM

The complete system is shown in figure 4 where the interferometer has been moved down to its focus position for the mirror under test on the polishing machine rotary table.

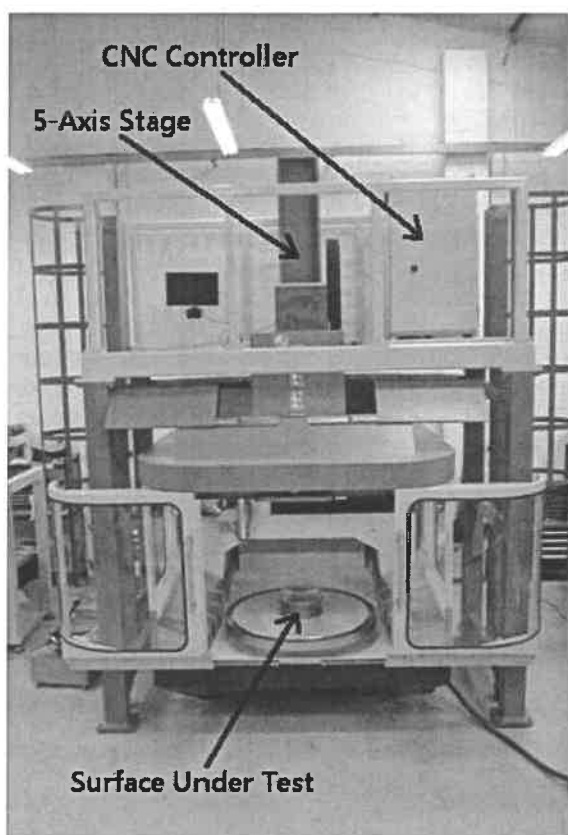


FIGURE 4. Complete system of IRP polishing machine, 5-axis CNC stage and Fizeau interferometer for on-machine testing.

Repeatability

The system illustrated was used on the machine shop floor to make measurements on a 460 mm diameter f/3.7 sphere before aspherization. As a quick illustration, two measurements were made

with each formed from the mean of 1024 measurements. The difference between measurements gives a very simplistic measure of the system repeatability in a shop-floor environment. Figure 5 shows a plot of the difference measurement.

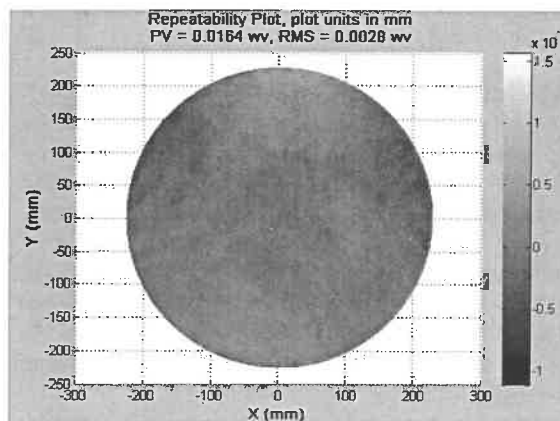


FIGURE 5. Short-term naïve repeatability plot for 4D FizCam 3000 on Zeeko CNC test tower with Zeeko IRP 1000 polishing machine servos active. PV measure is 10.4 nm and RMS measure is 1.8 nm. Difference of 2 averages of 1024 measurements.

A better estimate of the repeatability was made from using 12 measurements, each an average of 256 measurements. This has established the results shown in table 2. The results were derived from measuring the f/3.7 sphere on the polishing machine table with the IRP servos energized.

TABLE 2. Repeatability and precision results from measurement of the f/3.7 sphere.

Statistic	Calc.	Result
PVq repeatability	Standard dev. of PVq	0.0135 wv
RMS repeatability	Standard dev. of RMS	0.0028 wv
PVq precision	Mean of delta PVq	0.0192 wv
RMS precision	Mean of delta RMS	0.0036 wv

The table shows the whole system to be acceptable if $\lambda/10$ PV and better optics are to be measured, subject to wavefront calibration.

Form Correction Results

The system was used to spherize the same 460 mm f/3.7 sphere prior to its aspherization. Targeting approximately 1 wave of error, the surface was taken down from approx 5 waves during a number of polishing runs. We had hoped to publish the aspherization results using a phase-type CGH but a defective part mounting precluded full aspherization in time.

EXTENSION TO CONVEX ASPHERES

A scheme was designed to measure a convex asphere using a plano transmission element and CGH. A CGH was procured from Diffraction International to partially measure a rotationally symmetric f/4.2 convex asphere of 180 mm diameter with 28 μm of departure. A support system was designed to mount the CGH to the interferometer cage on the 5-axis stage at the correct position relative to the part in the plano beam (figure 6).

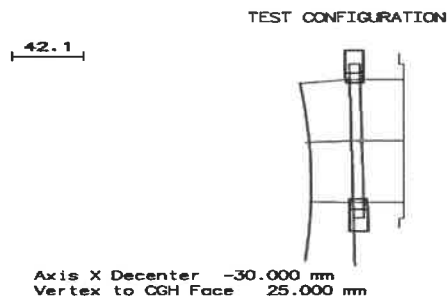


FIGURE 6. From left-to-right: Surface under test, CGH element and plano transmission sphere.

The CGH was designed to measure the area of the part shown in figure 7. By appropriate positioning of the CGH and interferometer system, the mirror can be measured by stitching together sub-apertures acquired by rotating the part under the interferometer-CGH pair, about its vertex (figure 8) using the IRP rotary table.

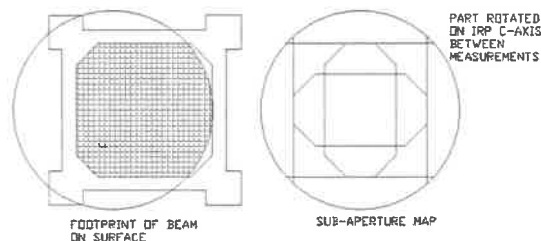


FIGURE 7. Area of convex mirror measured by single CGH measurement, and a diagram showing how the full surface can be measured

by rotating the part under the interferometer-CGH pair.

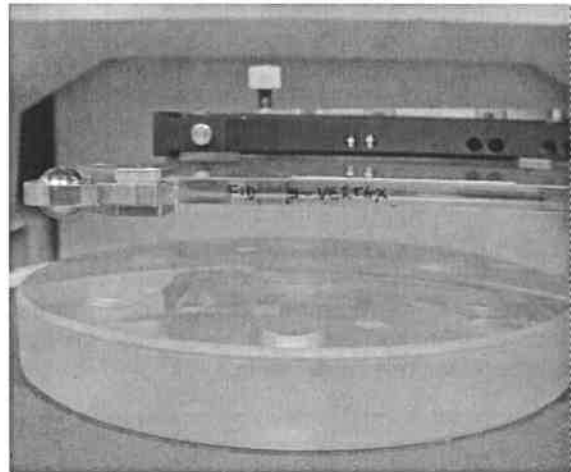


FIGURE 8. Phase-type CGH and convex asphere undergoing sub-aperture measurement.

We used our own software to stitch the sub-apertures together and produce a synthetic full-aperture map. This map was subsequently used for a corrective polishing run after removal of rotationally symmetric and $2n\theta$ azimuthal terms. A single correction took the form from 4.4 μm down to 0.7 μm (figure 9). Better control of systematic and alignment errors has enabled us to reduce this error and to keep the rotationally symmetric and $2n\theta$ terms in the sub-aperture data resulting in better stitched data maps.

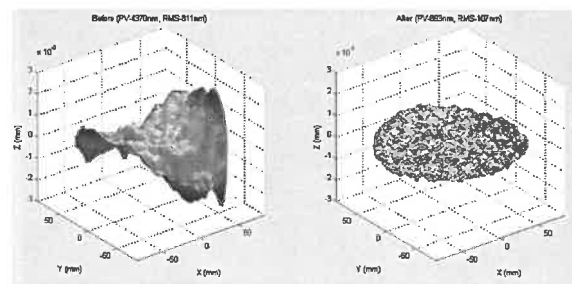


FIGURE 9. Left: stitched measurement result before corrective polishing. Right: stitched measurement result after corrective polishing. Both plots are at the same scale where the mean sub-aperture was subtracted from from each sub-aperture measurement before stitching.

Figure 10 shows the stitching result without removing the rotationally symmetric and $2n\theta$ terms via average subtraction.

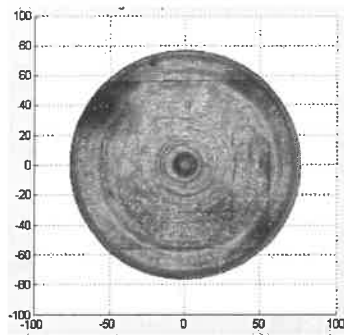


FIGURE 10. Full stitched measurement result for the convex asphere including rotationally symmetric and $2n\theta$ terms. PV is 1.1 μm and RMS is 99 nm. Some stitching errors remain at a few 10s of nm in this plot.

Our aim with the method is to bring the part errors down to $PV = 80 \text{ nm}$ ($\lambda/8$) by successive refinement of the hardware and software.

Stitching Software

The stitching software developed allows for any number of sub-aperture maps distributed around 360 degrees and works via two algorithms. The first is a least-squares fit [2] to the overlap regions that resulted in the data shown in figure 7. A second algorithm under development uses a Maximum Likelihood Method [3], to estimate the surface errors, the reference optics errors and the ambiguous errors. At present, the MLE method shows good quantitative agreement with the least-squares algorithm.

WHITE LIGHT INTERFEROMETRY

As we are developing complete on-machine optical surface characterization system we also looked at the requirements for texture measurements (roughness) using white light interferometry. In collaboration with 4D Technology we are developing on-machine white light texture interferometry for use on the Zeeko IRP machines and other platforms. The advantage of such an in-situ system is clear when large parts are considered: the part can remain on the polishing machine during measurement. This also obviates the requirements for a replication process to measure the surface roughness and the associated difficulties with finding a reliable replication process.

The Zeeko Surface Texture Analyser 1 has been designed by, and in collaboration with, 4D Technology and uses 4D's patented system for vibration immunity[4]. The instrument has a X10 Linnick objective, controls for field stop, f-stop and beam balance, and operates using 4Sight software or using Zeeko's on-machine software currently under development.

FIGURE 11 shows the STA1 undergoing early trials at Zeeko Research in May 2010 where it is mounted onto a 4-axis CNC system used to simulate the IRP polishing machine's linear axes.

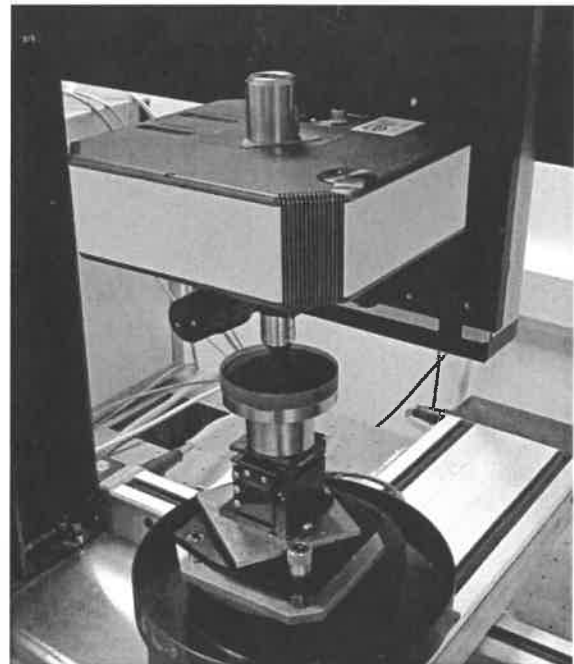


FIGURE 11. Zeeko STA1 mounted on CNC controlled development rig. At the top of the interferometer is a 40 mm spigot that interfaces to the Zeeko IRP series of polishing machines.

Repeatability

As part of the initial testing we measured the surface of a smooth flat using the STA1 on a standard workbench to establish the repeatability. Table 3 shows the RMS repeatability as a function of the number of measurements averaged. Each measurement is the average of # measurements (column 1).

TABLE 3. Repeatability and precision of the measurement results obtained with STA1 on a standard lab workbench with no vibration isolation.

# meas averaged	RMS (nm)	RMS repeatability (nm)	RMS precision (nm)
2	0.301	0.055	0.3700
4	0.282	0.023	0.236
8	0.251	0.026	0.200
16	0.248	0.012	0.119
32	0.244	0.003	0.078

Step Height Measurement

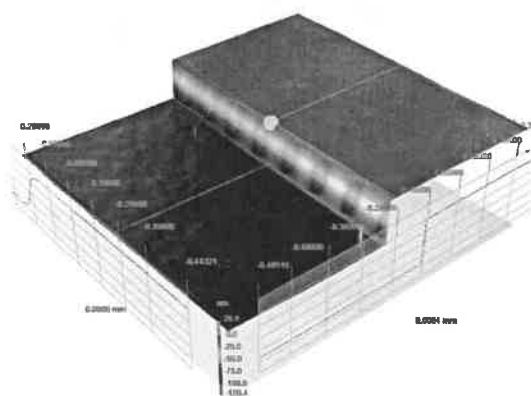


FIGURE 12. Step height measurement using the Zeeko STA1. Step height is nominally 91 nm. STA1 measured the height as 94.46 nm.

A nominal 91 nm step was measured using STA1 on the workbench and this was compared with a measurement result with a Veeco instrument. The STA1 value was found to be 94.46 nm, whilst the measurement on the Veeco system revealed 92.92 nm. One possible cause of the discrepancy is the calibrated wavelengths of one or both instruments may be off by a percent or so. However, the initial results from STA1 look promising.

CONCLUSION

We have described an automated CNC system for the on-machine interferometric metrology of large (up to 1 m diameter) spheres and aspheres utilizing an optical test tower, Fizeau interferometer and CGH elements. In addition, we have shown some results using this instrumentation to stitch sub-aperture measurements on a rotationally symmetric convex asphere. We have used this system to perform corrective polishing and found that we can achieve repeatabilities of the order of

$\lambda/60$ PV with only a modest amount of averaging.

We have also shown initial results from our new development in on-machine texture measurement for larger optics which shows good promise.

We hope to expand upon all these results and developments in a future paper on the subject.

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RETRACE AND PROPAGATION ERROR IN A NON-NULL INTERFEROMETER

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Non-null interferometers measure optical surfaces or components by means of partially compensating systems. A common application is the measurement of weak aspheres by means of a transmission sphere. Other applications include the testing of free form surfaces by means of rotational symmetric null-systems or the test of aspheres with a sub-aperture collecting spherical interferometer device. In any of these cases mainly two optical effects will limit the achievable accuracy of the instrument:

1. Propagation error
2. Retrace error

When an aspherical wavefront propagates through free space, it continuously changes its shape. This can lead to propagation errors, since the camera will not measure the wavefront that originated at the aspherical surface. This effect can be almost eliminated by placing the asphere close to the focal plane or by software correction of the measured wavefront.

The retrace error in an interferometer occurs, when rays returning from the test surface follow a path considerably different from the path in calibration situation. A calibration is usually carried out by means of a good quality spherical surface which is well adjusted, such that only very few fringes are seen by the camera. Rays from reference and test surface then follow basically identical paths.

Retrace errors are driven by:

- Design limitations
- Figure error and imperfections of the optical surfaces in the interferometer
- Misalignment of optical components

Depending on the cause this can lead to distortions and/or phase errors in the measured wavefront, which mostly depend linearly on the steepness of the asphere.

In this talk we will present a software correction method for propagation errors and a method to compensate high- and mid-spatial frequency retrace errors. These are mainly caused by figure errors and imperfections of the optical elements in the measurement apparatus. Our calibration algorithm allows to calculate the expected retrace error in non-null measurements and to subtract it from the actual measurements, improving the accuracy of the interferometer considerably.

FORM MEASUREMENT OF COMPLEX FREEFORM SURFACES BY TILTED INTERFEROMETRY

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1: INTRODUCTION

This paper will focus on the use of the use of tilted interferometry in the form metrology of complex diamond machined optical surfaces. The surfaces in question are complex freeform surfaces machined in aluminium for application in astronomical instrumentation. In principle, diamond machining is capable of the precise replication of any surface that can be mathematically defined, regardless of symmetry constraints. This combination of precision and flexibility empowers optical designers to generate powerful, novel and unorthodox designs. Unfortunately, this freedom comes at a price. The complexity of these freeform surfaces creates substantial difficulties in the accurate measurement of their form. This is a serious issue since form characterisation and metrology plays an essential role in the improvement and verification of the manufacturing process.

Computer generated holograms (CGH) [1] have been applied to the measurement of genuinely freeform surfaces with large aspheric departure. These holograms are used to create phase departures that cancel out those produced by the freeform departure of the surface under measurement. Unfortunately, the generation of CHG is both costly and time consuming and the technique is generally applied to low volume, high value optics. The tilted interferometry technique discussed here [2], [3] is more flexible and can be applied to a range of different components with significant freeform departure. For a majority of the freeform surfaces produced at this laboratory, the second order astigmatic terms dominate; higher order terms are generally restricted to a fraction of a wavelength. As such, the challenge is to measure the absolute value of the astigmatic departure to ± 5 nm, where the total astigmatism may be 20 μ m peak to peak or greater.

The arrangement adopted here is based on a double pass, tilted Twyman-Green

Interferometer arrangement [4]. This off-axis arrangement is used to 'null out' the astigmatism of the surface, enabling accurate characterisation using a spherical wave. Although this technique is currently limited to astigmatic surfaces, as opposed to more general freeform surfaces, it remains generally applicable to 'slower' optics, where the numerical aperture is limited. In the case of slower optics, it may be reasonable to approximate a freeform shape to a second order polynomial, with acceptable (less than one fringe) residual error remaining in higher order terms.

Particular emphasis here will be placed on the extension of the technique to the measurement of higher order form departures. By varying the geometrical arrangement, it will be possible to characterise accurately form departures described by third order polynomials, such as coma and trefoil. This would further extend the application envelope of this technique.

2: TILTED INTERFEROMETRY

2.1: Basic Measurement Technique

Phase shifting interferometry is widely used in the measurement of surface form. Most specifically, the arrangement adopted here is based on the Twyman-Green Interferometer. Precise measurements of optical surface form are possible by using high fidelity reference surfaces, e.g, flats or spheres, to calibrate out wavefront errors in the interferometer optics. Calibration is effected by subtracting the apparent form of the reference surface from subsequent readings.

The calibration procedure does, however, assume that the system under test does not produce substantial distortion in the returning wavefront. Negation of this assumption invalidates the calibration procedure. As a consequence, accurate form measurement is only possible if the overall wavefront distortion is

limited to a few fringes. Therefore, in the case of a highly astigmatic surface, as shown in the interferogram in Figure 1, where there is substantial distortion, accurate measurement is not possible using a conventional test set up. However, by tilting the test set up to counteract the astigmatism of the part, it is possible to use test and return wavefronts that are approximately spherical.

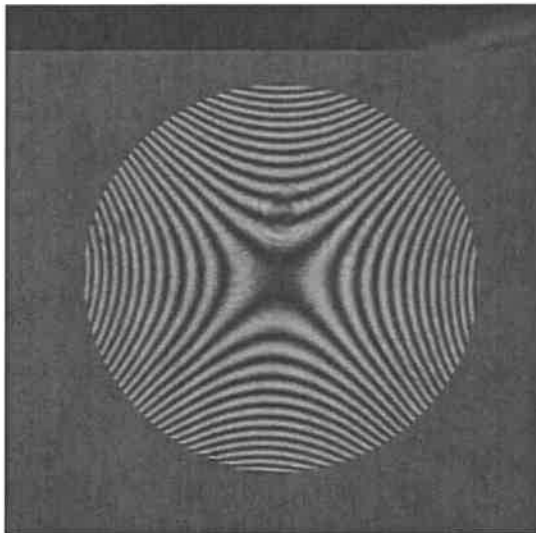


FIGURE 1. *Basic Interferogram of Astigmatic Surface*

The principle behind this technique is that the astigmatic surface itself may be approximated to the section of an ellipsoid with two foci. The focus of the interferometer is placed at one of these foci and the centre of a reference

reflecting sphere at the other. Figure 2 shows the basic arrangement, with the component placed on a turntable and the reference sphere on a linear stage. It is clear from Figure 2 that the arrangement is a double pass set up, with the beam impinging on the test piece twice.

By rotating the part and moving the sphere on its linear stage, it is possible to precisely 'null out' the astigmatism. It is important to note that there are two component tilt angles, $\pm\theta$ at which this 'nulling out' occurs; the relative positions of interferometer focus and reference sphere centre are reversed. Using the linear stage, it is possible to measure the displacement between these two positions very accurately. This is achieved by plotting the astigmatic Zernike polynomial [5] component against reference sphere displacement and determining the intercept for each focus. Having measured the base radius of the component, the astigmatic contribution may be calculated to great accuracy. This approach substantially reduces sensitivity to alignment errors.

The procedure allows the measurement of the astigmatic component, which may be tens of microns peak to peak, to an accuracy of a few nanometres. Residual, higher order form may be determined from the optimized interferogram, taken in the tilted set up. In computing the residual mirror form, it is important to recognise that the system is a double pass set up, so that any wavefront error produced would be double that observed in a single pass set up (*for the same form error*).

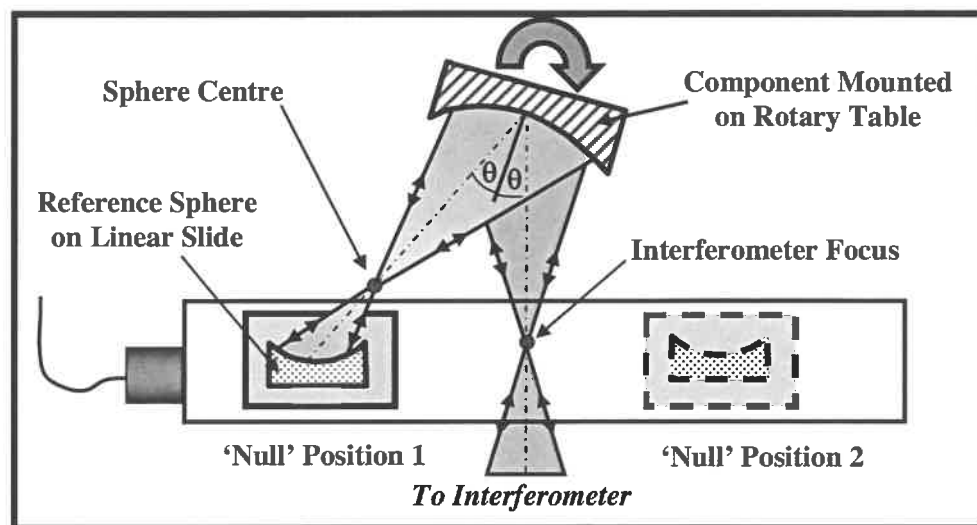


FIGURE 2. *Basic Tilted Interferometry Arrangement Showing Two 'Null' Points*

2.2: Simple Model for 'Slow' Optics

Introduction of tilt into systems produces off axis aberrations. In this case of tilted interferometry, these aberrations are exploited to offset form departures present in the test piece. For the case of a symmetrical system, with the object and image distances identical, the effect of tilt is to add astigmatism to the system. However, where the object and image distances are not identical, third order coma is also added. A very simple model of a test scenario is sketched in Figure 3.

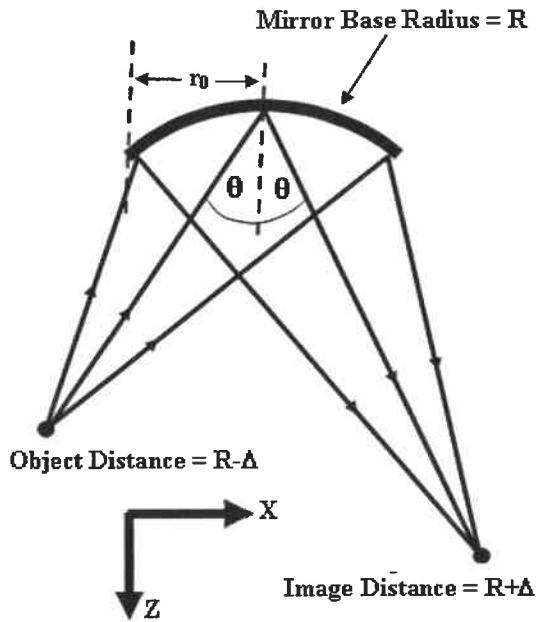


FIGURE 3. Simple Model of Test Scenario

It is straightforward to calculate the wavefront error as a function of the aperture co-ordinates, (x, y) . In this analysis, only wavefront terms up to third order in aperture are included. This approximation is valid where the aperture is relatively small, i.e. for 'slow' optics. The wavefront distortion contains two terms:

$$1) \quad \Phi = \frac{(x^2 - y^2) \sin^2 \theta}{2R} + \frac{x(x^2 + y^2)}{R^3} \Delta \sin \theta$$

Φ is the wavefront error. All other symbols are as in Figure 3.

The first term is the astigmatic term and is dependent only upon the tilt angle. The second term is the coma term and is proportional to the displacement from equidistance, Δ , and the sine of the tilt angle. Equation 1) may be used to

calculate the RMS magnitude of the relevant Zernike terms, for a component, as in Figure 3, of radius R .

$$2) \quad \Phi_{astig} = \frac{r_0^2 \sin^2 \theta}{\sqrt{24}R}$$

$$3) \quad \Phi_{coma} = \frac{r_0^3}{\sqrt{72}R^3} \Delta \sin \theta$$

2.3: Third Order Form Departure

In its original inception, tilted interferometry is capable of characterising an second order anamorphic freeform surface. The previous discussion suggests that it is possible to extend the technique to third order form departures. Indeed, it is clear that by using (and characterising) unequal object and image distances, then coma may be measured. However, this does not encompass the remaining group of third order departures, the trefoil terms. In this case, the form departure is proportional to $\sin 3\theta$ or $\cos 3\theta$. One possible approach to this difficulty is to use anamorphic magnification to expand the pupil in one direction. This could be achieved, for example, by using a prism beam expander to magnify a collimated beam along one axis. The effect of this expansion would be to partially transmute the coma into trefoil, by an anamorphic magnification of a factor of b in the y direction:

$$4a) \quad \Phi = \xi x(x^2 + b^2 y^2)$$

$$4b) \quad \Phi = \frac{3+b^2}{4}(x^3 + xy^2) + \frac{1-b^2}{4}(x^3 - 3xy^2)$$

The second term on the RHS of 4b) is the trefoil term. Although this does not cover fourth order form deviations, the extension to third order form departures further enhance the application of tilted interferometry.

3: TYPICAL RESULTS

3.1: Simple Astigmatic Optics

A simple astigmatic component was measured using a tilted arrangement, as previously described. The interferometer was a FISBA μ 2HR Phase Shifting Twyman-Green Interferometer. A typical optimised interferogram is shown in Figure 4; the component is exactly the same as that illustrated

in the conventional interferogram depicted in Figure 1. It is important to note the substantial reduction in the wavefront distortion when compared to Figure 1. Table 2 shows the measurement results for a typical component. The component is a highly astigmatic mirror, about 15 mm in diameter with a base radius of about 227 mm; the astigmatic component is about 1.2 μm RMS. This component was produced from aluminium by a freeform diamond machining process. Table 2 splits the form components and errors into Zernike polynomials, with the numbering convention as per Noll [6].

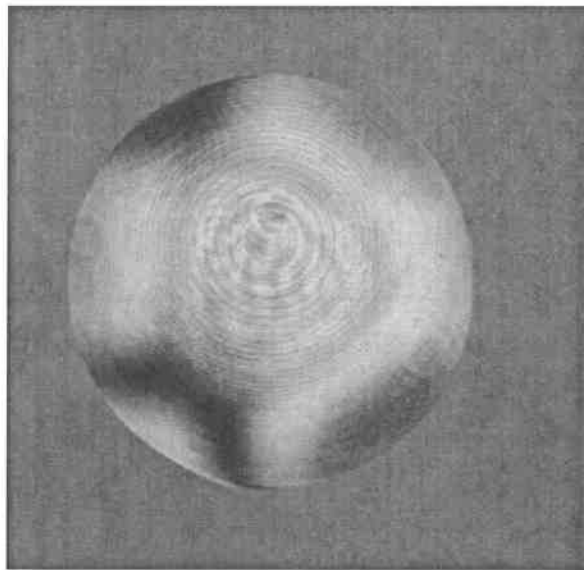


FIGURE 4. Typical Optimised Interferogram

The overall form error is very small, being less than 15nm. This is typical of components of this type using this machining process. Overall, the uncertainty in the measurement amounts to ± 5 nm RMS. Much of this uncertainty is associated with the mechanical alignment of the part, and could be further improved.

3.2: Impact of Coma

As discussed in section 2.3, changing the distance, R , from interferometer focus to test piece will, in a tilted arrangement lead to variation in coma. To this end, a simple

experiment was conducted using the test piece described in 3.1. Whilst in a tilted arrangement, the distance from component to interferometer was varied and the RMS coma term was recorded into a mask of nominal radius of 6.02 mm using the interferometer data processing software. The results are shown graphically in Figure 5. This shows, as expected, a clear linear trend in coma with defocus. There is, of course, a bias term, which represents the coma that is inherent in the form of the part. The gradient of the plot, at 0.60 nm per mm is close to the theoretical value of 0.54 nm per mm. The small discrepancy is probably due to a system calibration error in defining the 6.02 mm mask, caused by a bias in the interferometer lateral magnification amounting to about 3%.

TABLE 1. Form error of typical astigmatic part expressed in nm RMS and broken down into Zernike components with a normalization radius of 6.02 mm

Zernike Term	Measured (nm)	Design (nm)	Error (nm)
Z5	-6.26	0	-6.26
Z6	-1177.13	-1169.8	-7.33
Z7	1.09	0	1.09
Z8	-6.24	-5	-1.24
Z9	-0.56	0	-0.56
Z10	16.79	16.4	0.39
Z11	-2.63	2.2	-4.83
Z12	2.22	1.5	0.72
Z13	-0.14	0	-0.14
Z14	1.94	1.2	0.74
Z15	0.30	0	0.30
Z16	0.32	0	0.32
Z17	-0.11	0	-0.11
Z18	0.43	0	0.43
Z19	0.22	0	0.22
Z20	-0.17	0	-0.17
Z21	-0.26	0	-0.26
Remainder	3.96	0	3.96
TOTAL			11.70

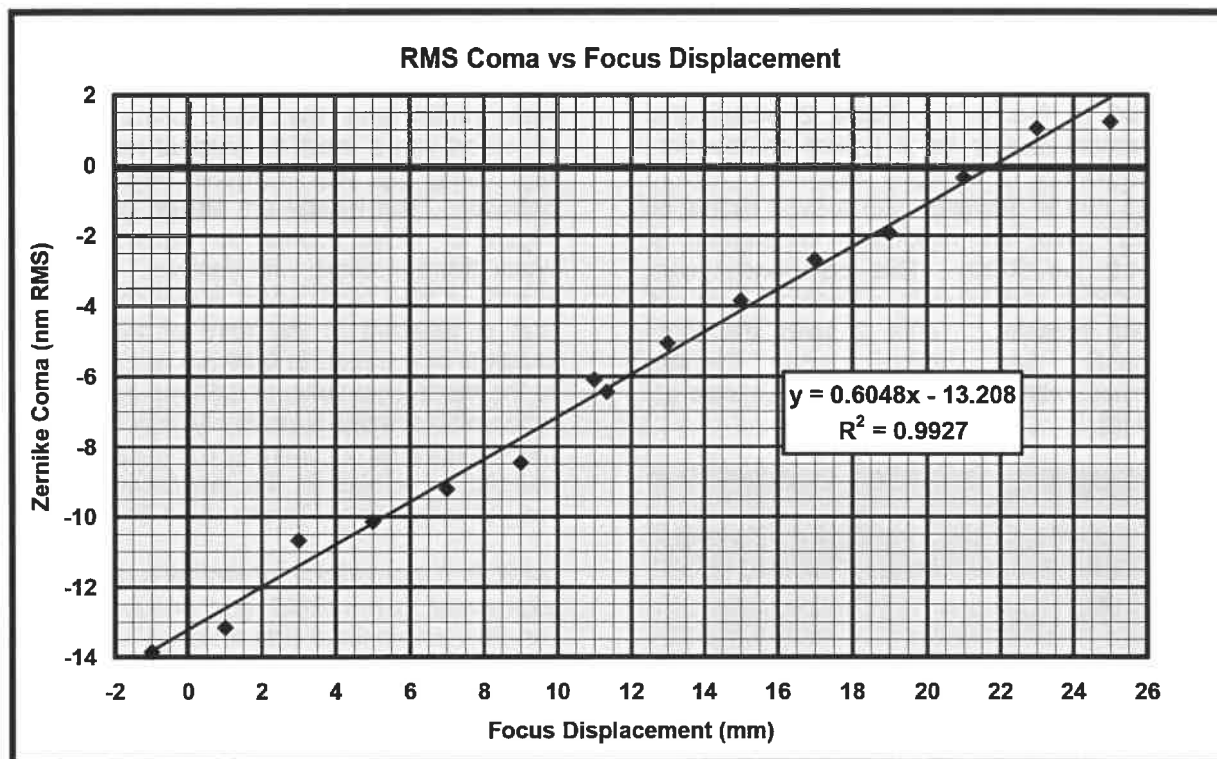


FIGURE 5. RMS Coma versus focus displacement for tilted astigmatic component. This clearly shows linear dependence of coma on defocus in a tilted system

4: DISCUSSION & CONCLUSIONS

Tilted interferometry is a powerful technique for the form measurement of complex freeform surfaces. Although there is an apparent limitation to the measurement of astigmatic surfaces described by second order form deviation, for optics with moderate numerical aperture, this is not a serious handicap. The requirement is only that the higher order form departure be restricted to less than one or two fringes.

In principle, it is possible to extend the technique to the measurement of surfaces with large third order deviations. This would add some complexity to the measurement by adding extra degrees of freedom into the measurement. Nonetheless, this would offer the possibility of extending the application area to even more complex freeform surfaces.

Further opportunities could be provided by using sub-aperturing techniques to deal with very challenging surfaces. If it were possible to measure any third order freeform surface, then the effect of remaining fourth order form departure would be dramatically reduced by

sub-aperturing. Reducing the aperture size by a factor of two would reduce the fourth order contribution by a factor of 16. The surface would then be re-assembled by 'stitching' the sub-apertures together. This process would, in itself, raise many significant challenges. Nonetheless, it would offer the prospect of extending the use of tilted interferometry to cover even more complex and larger scale optics.

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MICRODEFLECTOMETRY AND STRUCTURED ILLUMINATION MICROSCOPY – NEW TOOLS FOR 3D-METROLOGY AT NANOMETER SCALE

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INTRODUCTION

We will introduce two new 3D-sensors to measure the 3D-topography of smooth and rough surfaces. Both sensors allow for a depth (z-) sensitivity at the nanometer scale. The sensors use spatially and temporally incoherent illumination and are not based on interferometry (but may occasionally compete with - or at least complement - interferometry). They are robust and simple and (specifically μ -deflectometry) information theoretically efficient. With low noise and high depth of field they provide (quantitative 3D-) images with SEM-like quality.

MICRODEFLECTOMETRY

Microdeflectometry is based on the observation of mirror images of a remote pattern, where the surface under test is the “mirror”. The mirrored pattern is distorted, depending on the shape of the object. From the distortion, the local slope of the surface can be acquired. The full field measurement takes a few seconds. The basic principle is well known and already used for macroscopical metrology [1, 2, 3, 4]. One major application is the measurement of aspherical eye glasses [5].

Deflectometry intrinsically acquires the slope – rather than the shape. This is an information efficient process [6]: the stand off distance is not measured, only the “useful” information is acquired. That is why we can achieve nanometer sensitivity in presence of 10 mm depth range.

We adapted deflectometry for a microscope. Details are described in [7]. The basic apparatus and its working principle are sketched in Fig. 1: We project an aerial image of the fringe pattern at a distance d from the object. A point M at the object surface is imaged by a cone of rays, represented by the dark grey area. The observed image intensity is given by the

intensity within this cone, averaged over the distance δb . This averaging is due to the defocused pattern imaging. The imaging cone depends on the slope α . The observed phase ϕ in the image plane depends on the slope, with $\phi = 2\pi d \alpha / p$, with the fringe period p .

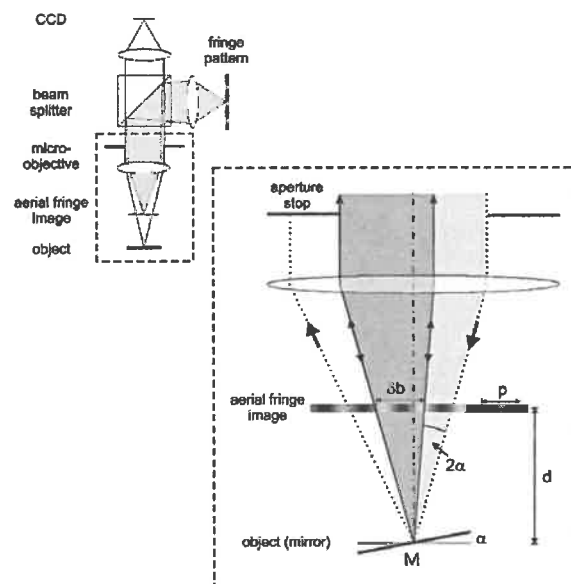


FIGURE 1. Schematic setup and working principle of microdeflectometry.

We will now explain why deflectometry displays high sensitivity against slope variations and where the limits are.

Deflectometry displays high slope sensitivity

The high slope sensitivity follows from an uncertainty relation derived in [2, 7]:

$$(1) \quad \delta x \cdot \delta \alpha = \lambda / Q$$

Where δx is the lateral diffraction limited resolution and $\delta \alpha$ is the physical angular measuring uncertainty. Q is a quality factor, depending on the camera noise. Equation (1) appears a little disappointing since we learn that with higher lateral resolution (with higher aperture) the slope uncertainty will become bigger. However, if we put in the experimental value of $Q \sim 1000$, we get approximately

$$(2) \quad \delta x \cdot \delta \alpha = 1 \text{ nm}.$$

The minimum detectable height variation δz within the diffraction-limited resolution distance of the microscope is constant and in the range of only 1 nm. Q depends only on the camera noise, it can be increased by photon averaging. So a much higher depth sensitivity can be achieved, or – with bigger δx – a very high angular sensitivity. The latter was impressively demonstrated by the so called ESAD method, described in [8].

Is Equation (2) still valid for high-aperture microdeflectometry? The reader might doubt, since we select the magnitude of distance d greater than one hundred times the dof. The large distance d keeps the relative change of d (caused by height variations of the object) small. Yet the result of our experiments [7] demonstrates that the relation is valid even for very high aperture and a very small dof. This is possible because we scale up the fringe period p linearly with the distance d . In order to maintain a high contrast in the observed fringe image, the distance δb must not exceed $p/2$.

EXAMPLES

We will present only one example here, more can be taken from [7].

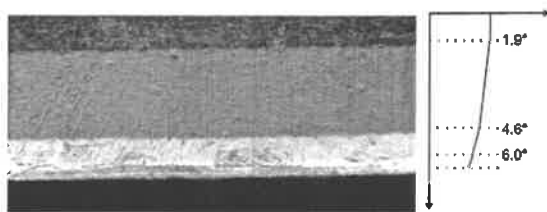


FIGURE 2. Intensity encoded slope map of a razor blade (slope in vertical direction).

We will conclude the section about microdeflectometry with some remarks about its intriguing features:

The inherently measured signal is the slope. Slope encoding is what makes differential interference contrast and SEM images so impressive. SEM images, in addition, display a high depth of field. The same is true for microdeflectometry images (depth expansion is possible as well). The slope encoding enhances extremely small depth variations of the surface (down to the nanometer). From the slope, the shape $z(x, y)$ can be calculated with extremely low noise [9], since integration is a noise-suppressing operation. (We admit that steps at an object surface cannot be measured).

The noise level is small. Microdeflectometry can be implemented with high illumination aperture, so residual coherent noise artefacts will have low contrast. Moreover, high aperture enables a high dynamical range of the slope measurement. In our experiments we achieved an angular dynamical range of up to 2500. This is much better than what can be achieved in intensity images.

The small dof is a major drawback of microscopic imaging. It is intriguing and a challenge to create SEM-like images (large dof) optically, with microdeflectometry. We demonstrate in [7] that this is possible by combining microdeflectometry with the expansion of the dof. To finish the eulogy with a critical remark: microdeflectometry measures the derivative of the shape, hence the low frequency information is difficult to measure, with high accuracy. Nevertheless, microdeflectometry is simple, incoherent, and – has the potential to compete against interferometry, at least for aspheric and steep surfaces.

We will now proceed to another sensor principle, based on a very similar technology, but with a different signal generating mechanism.

STRUCTURED ILLUMINATION MICROSCOPY

Structured illumination microscopy (SIM) is, principally, a long time known concept [10, 11]. Surprisingly, it was, to our knowledge, not really exploited for technical metrology, until recently. The basic idea is simple and based on focus sensing. The SIM concept is comparable, to a certain extent, to confocal microscopy. A fringe pattern is projected onto the object surface, the object is observed by a camera. The local contrast $C(x, y)$ will be measured – for example, by phase shifting. $C(x, y, z)$ will be stored, while the object is scanned along the z -axis, through

the focus of the microscope. From the maximum of $C(z)$, the object shape can be acquired.

SIM displays interesting features, similar to microdeflectometry: it is an incoherent (low noise) technique. The local depth resolution is in the nanometer regime, for smooth objects. The angular range of the slope can (principally) be as large as the microscope aperture angle. The possible depth of field may be larger than 100 times the Rayleigh dof. The difference between SIM and deflectometry is that SIM measures the *shape* instead of the *slope*. So the low spatial frequency content is maintained by SIM.

We will briefly display some results from [12] to demonstrate how powerful SIM is, and will then discuss the limitations.

MEASUREMENTS WITH SIM

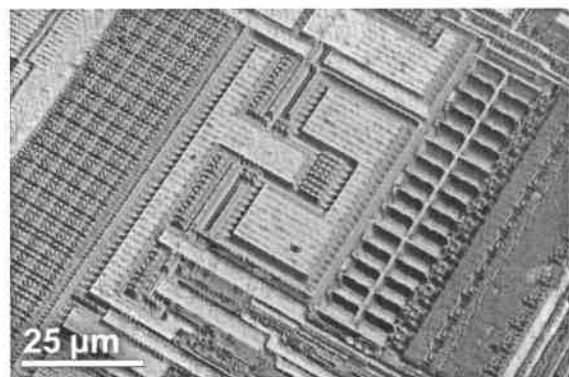


FIGURE 3. SEM-like image of a wafer generated by structured illumination microscopy

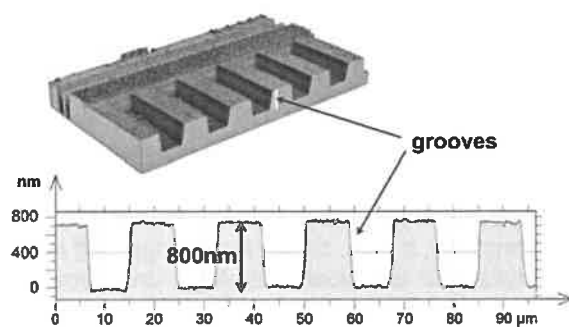


FIGURE 4. Quantitative 3D-data from the object shown in Fig. 3.

Figures 3 and 4, taken with a 50x0.80 microobjective, display a depth of field larger

than the Rayleigh depth, and only about 20nm depth noise. (A fraction of that “noise” may even be part of the true surface topography).

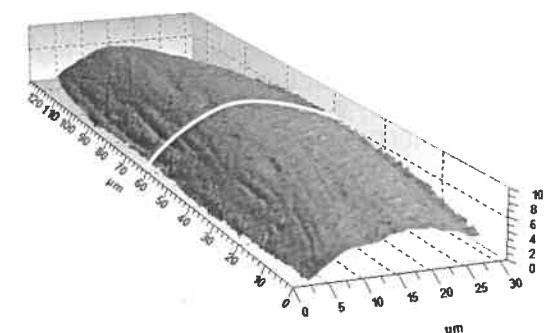


FIGURE 5. SIM data (50x0.80) from a touch probe tip. This experiment demonstrates that it is possible to measure strongly curved surfaces with large dof and sub micron global accuracy. The lateral and longitudinal scales are identical, to display the angular dynamical range.

Physical limits of SIM

Figure 6 displays the contrast function $C(z)$ for one pixel.

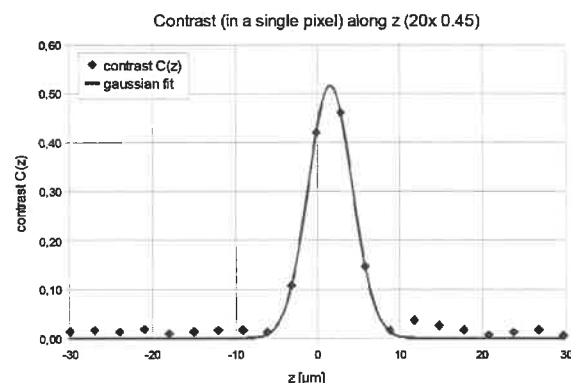


FIGURE 6. Observed contrast $C(z)$ versus depth position z , with microscope objective 20x0.45. Note that the width of $C(z)$ can be scaled by the chosen fringe period of the projected pattern and by the aperture.

By interpolation, it is possible to locate the maximum with a few nanometers uncertainty. The uncertainty δz depends on the noise. For smooth surfaces, the ultimate source of noise is photon noise, which can be reduced by averaging (using many photons), so there is virtually no lower limit for δz .

Figure 7 displays the physical measuring uncertainty at a smooth surface, versus the numerical aperture of the projection and observation. The red curve approximately represents the Rayleigh depth of field divided by the signal-to-noise ratio of the camera.

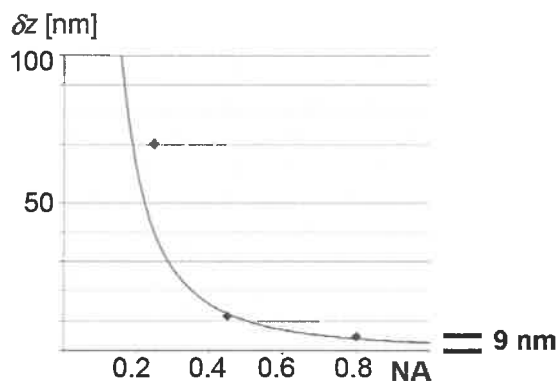


FIGURE 7. Physical measuring uncertainty δz at a smooth surface vs. numerical aperture. The red curve approximately represents the function: $\text{Rayleigh dof}/\text{SNR} \sim 1/\text{NA}^2$.

SIM works at smooth and rough surfaces. This is not the case for deflectometry – the latter working only at smooth surfaces, and not for passive focus sensing, - which does not work on smooth surfaces.

For all triangulation methods, the major source of noise at rough surfaces is speckle noise [13], and not anymore photon noise. So it is for SIM - at rough surfaces. The severe consequence is that the physically achievable measuring uncertainty is much bigger than for measurements at smooth surfaces, as shown in Fig. 8. We measured the topography of a planar surface with a known roughness of 800 nm. We repeated this with different NA and evaluated the standard deviation δz of the measured heights for each NA. For high NA, δz is almost equal to the surface roughness, and the measurements represent the true surface. For

low NA, the measurement displays a larger δz , and the true surface data are hidden by unavoidable noise.

With high aperture, the physical measuring uncertainty approaches the sub-micron range.

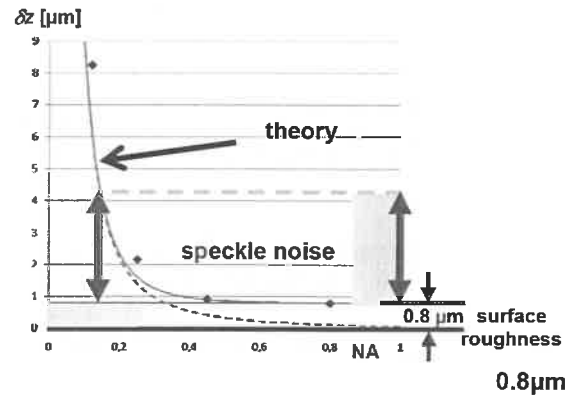


FIGURE 8. Physical measuring uncertainty δz at a rough surface with $0.8\mu\text{m}$ roughness, vs. numerical aperture NA. The red curve corresponds to the theoretical contribution of the speckle noise according to ref [13].

We summarize this result: With SIM we can achieve a depth measuring uncertainty on smooth surfaces which is limited only by photon noise. An uncertainty of 1-10 nm can easily be achieved.

At rough surfaces, the achievable minimum depth uncertainty is much larger, since it is limited by speckle noise.

SIM AND MICRODEFLECTOMETRY VERSUS INTERFEROMETRY ?

Both methods display advantages and drawbacks: Microdeflectometry is extremely sensitive against slope variations (small defects), but it is difficult to acquire the low frequency content, with high accuracy.

SIM is less sensitive against slope gradients, but has the potential to measure the global shape with high accuracy. This is demonstrated in Fig. 5 and Fig. 9. Figure 9 displays the measurement of a small bearing ball (radius 2.38 mm). It is not a fully calibrated measurement, but the deviation from the reference sphere is only $\pm 250\text{nm}$.

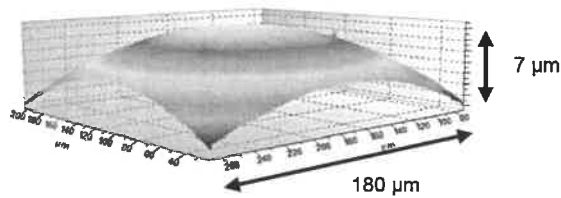


FIGURE 9. SIM measurement of a bearing ball with 2.38 mm diameter. The deviation from the sphere is less than ± 250 nm.

This deviation possibly stems from the field curvature of the microscope. The deviation is larger than that we are used to from interferometry. However, there is considerable room for improvement in favor of SIM: Although the design of a calibration procedure aiming for a global accuracy better than 100 nm for a field of up to 1000 μm and for steep slopes is a challenging task, it should be possible. We would like to mention that we achieved a global accuracy of 1 μm over a field of 80 mm with our macroscopic deflectometry setup.

So it appears that SIM has the potential to measure micro-lenses. For strongly curved surfaces and for aspheric lenses SIM and microdeflectometry definitely will compete with, or at least complement interferometry. This makes us optimistic to scale up SIM in order to measure macroscopic lens surfaces ("Structured Illumination Macroscopy").

As demonstrated, the sensitivity of both methods (SIM and microdeflectometry) can easily be driven to the nanometer regime, thus being able to compete with interferometry. There is one more analogy to interferometry: The contrast curve $C(z)$ of Fig. 5 can be considered as the analog of the correlogram envelope $C_{\text{WLI}}(z)$ of white light interferometry (WLI). In WLI, the length of the correlogram corresponds to the coherence length of the illumination. In SIM, the length of $C(z)$ can be adapted, from a few micrometers to the mm-range, by simply choosing the proper aperture and the spacing of the projected fringes.

The big difference within this analogy is in favor of SIM: in WLI, the correlogram is modulated with $\lambda/2$ period. This requires sampling of the contrast function with very narrow z -steps and

further to demodulate the correlogram, to get the envelope $C_{\text{WLI}}(z)$. The necessity to acquire many raw images makes WLI slow and information theoretically inefficient, at least for objects with a big depth. Although it is possible to overcome this difficulty to a certain extent [14], and although the accuracy competition still is in favor of interferometry, it appears that SIM could at least become the more flexible and faster method.

CONCLUSIONS

The suggested sensors based on structured illumination microscopy or deflectometry both have intriguing features: They are incoherent, they are not based on interferometry with its known drawbacks. SIM works at rough and smooth surfaces. Since the sensors do not suffer from depth of field limitations, we can use very high aperture imaging, to achieve the highest possible lateral resolution and slope dynamics, even for objects with large depth range.

Measurements can be done within a few seconds. The (simple) technology to implement SIM is the same as that for microdeflectometry. So both principles can be combined within one microscope. SIM measures the shape (local distance) while microdeflectometry measures the local slope.

However, we will not conclude without coming back to the most beautiful and intriguing property of both methods: they supply images with very low noise and very large depth of field, and with at the same time diffraction limited lateral resolution. The surface slope may vary within a large angular range. These features are the ingredients of scanning electron microscope images. Although we cannot beat the Abbe lateral resolution limit, we can see nanometer defects and at the same time height variations of hundreds of micrometers, even at steep slopes. So we think, with SIM and microdeflectometry we are close to acquiring beautiful images like the SEM can. Of course we will be limited by diffraction, yet we will have an advantage over SEM: our 3D-data are quantitative.

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SCOTS, AN ALTERNATIVE TO SURFACE TOPOGRAPHIC INTERFEROMETRY

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INTRODUCTION

The Software Configurable Optical Test System (SCOTS) is a method of testing optical surfaces that is functionally similar to interferometry but directly measures slopes rather than surface height. Initial experience with SCOTS indicates that the method has a dynamic range of at least 1:10000 in slope measurement, a dynamic range similar to interferometric surface topography. However, the equipment required for making a measurement is about 25 times less expensive than interferometry, and the test is much less sensitive to alignment and the environment.

In the paper the origins of the method will be reviewed and an explanation given of the current interest in the topic. We will describe the motivation for our interest and what we discovered about the method. Then we look at some theoretical limits of the process and give a list of some of the advantages over traditional interferometric methods of testing surface topography.

THE ORIGINS OF SCOTS

The idea of SCOTS goes back to the only tests opticians had for measuring topography prior to the laser and computers, namely slope measuring tests such as the Foucault knife edge, the Ronchi test which is several knife positions captured in a single image and the Hartmann test which was used to figure the 5m Mount Palomar primary mirror among others. [1]

The work described here was started independently from other work that dates back to at least 1954 in the German mechanical engineering literature [2] and has continued to the present. [3-7] One of the authors (Angel) was interested in an inexpensive and quick test of the solar concentrators he was making and realized that an up-scale laptop computer has all

the features necessary to do the job. It wasn't until we realized how well the method worked and submitted a paper on what we called SCOTS that an anonymous reviewer informed us that this method was well known in the literature, and there were patented applications of the method [8] and some commercial products [9].

This news did not deter us because we had discovered in the meantime that the method was very helpful in the making of precision aspheres. Furthermore, it also became obvious that while the fundamental method had been known for about 50 years that it has only been in the last few years that technology has advanced to the point where it is possible for almost anyone to implement the method and get wavefront measurements comparable in precision to traditional phase shifting interferometry. Again, 1 nm or better sensitivity has been pointed out in the literature [7] but not as applied to precision optics manufacturing.

DESCRIPTION OF SCOTS

SCOTS is a slope measuring test and may be most easily thought of as a Hartmann test in reverse, that is, in a Hartmann test a mask of holes on a regular grid is placed in front of the concave mirror under test and a point source of light is placed at or near the center of curvature. Light from the source reflecting off the mirror through the holes produces an array of spots in a plane near the center of curvature. It is easy to calculate where the spot should appear for a perfect mirror and displacements of the spots from the mirror under test tell what the slope errors are at the areas where there are holes in the mask.

In SCOTS, or any reflection deflectometric test, a regular array of straight lines on a screen positioned close to the center of curvature of a concave mirror will reflect off the mirror and

appear to a camera at the center of curvature as a series of distorted lines on the mirror surface. Knowing where a particular line on the screen was relative to the image of the line on the mirror surface allows one to calculate the slopes of the mirror surface perpendicular to the line [3] as shown in Fig. 1.

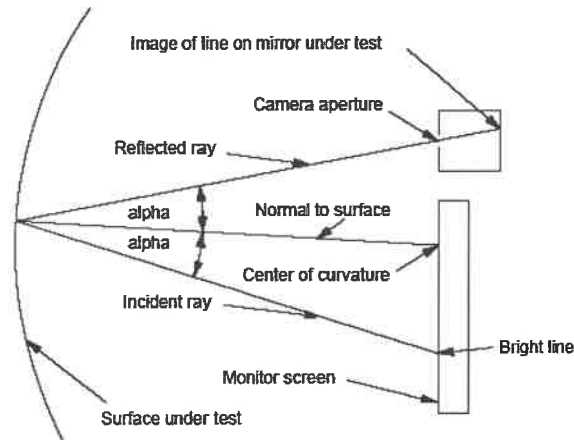


FIGURE 1. A schematic diagram of SCOTS, or reflection deflectometry. A bright line on the monitor screen reflects off the mirror and its image is recorded by the camera. The equivalence of angle of incidence and reflection allows solving for the normal to the surface.

As we said above, our original motivation was a quick, cheap method of measuring the shape of a solar concentrator. To that end we set up a screen and camera at the center of curvature of an off-axis segment of a parabola that was a trapezoid about 75 x 60 cm. The basic hardware using a smaller mirror is shown in Fig. 2

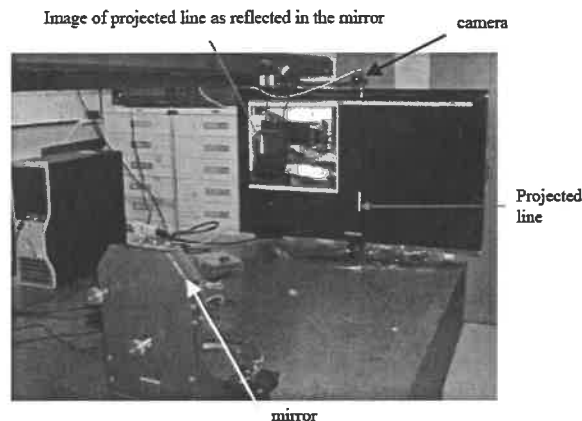


FIGURE 2. Screen with line and image of line as seen by the camera above the screen.

INITIAL SOLAR PANEL TEST

The hardware in Fig. 2 was a small mirror just to check out the set up. Once we put in the segment we were surprised to see the detail. Fig. 3 shows the x and y slopes from the segment after the linear term representing overall power was removed.

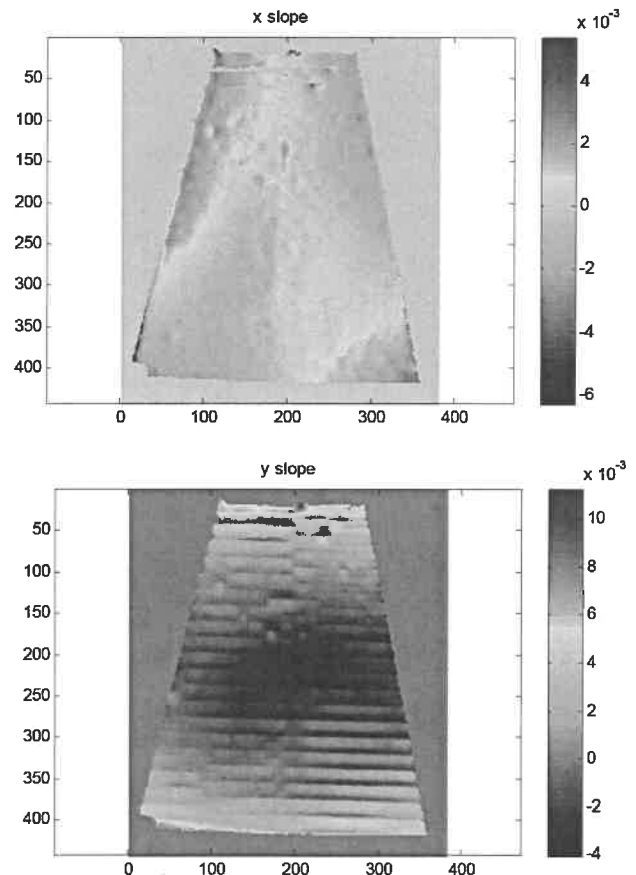


FIGURE 3. The x and y slopes of a molded off-axis parabolic segment after the overall power term was removed. The color bar scale is about 12 mrad p-v.

The linear pattern and line down the middle are real errors resulting from machining the mold. Rough scaling from these slope contour maps would indicate better than 1 mrad slope sensitivity over spatial scales of about 10 mm or better than 10 μ m height sensitivity. Analysis of the fit data indicated sensitivity closer to 1 μ m.

Thirteen of these panels were assembled into a 3 m diameter concentrator used as a collector demonstration experiment. A 40" LCD screen was placed at the center of curvature along with

a camera with a field of view of about 1 radian. Fig. 4 shows the hardware and a sample of the line pattern on the screen as reflected from the 3 m diameter, f/0.5 collector. In this test we had 10 μ radian sensitivity or a slope measuring dynamic range of 1:10000.

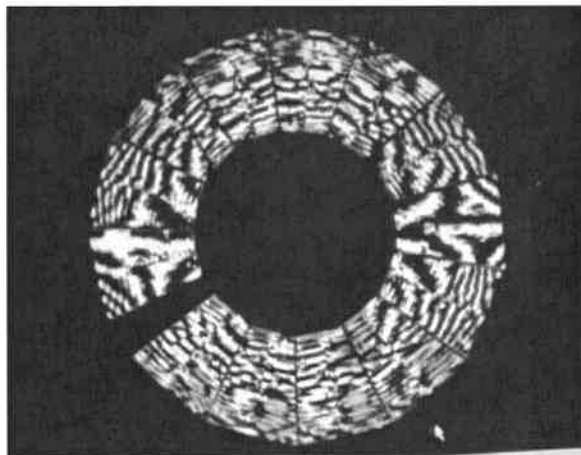
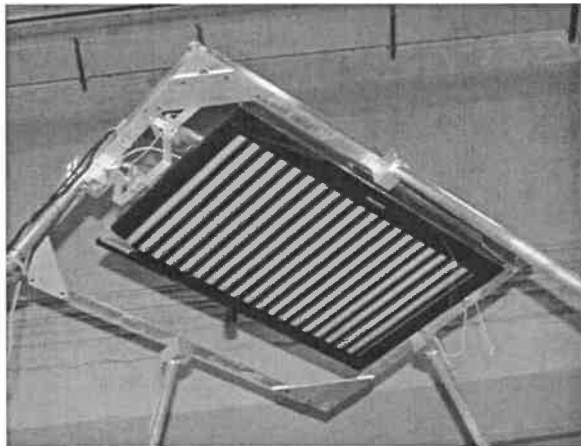


FIGURE 4. LCD screen above the concentrator and image of line pattern seen by camera.

There are at least 2 methods of displaying the pattern on the screen, a sinusoidal intensity pattern that can be shifted between camera exposures by $\frac{1}{4}$ fringe with the slope being retrieved with a 4 bucket interferometer algorithm, or by one bright square wave stripe at a time, first one direction and then the other and centroiding in software. Practical considerations may make one method or the other preferred.

Fig. 5 shows the slope data recovered from this collector. It is clear even from the line pattern that two of the segments are substantially out of alignment with the others. The slope data in Fig. 5 substantiate this.

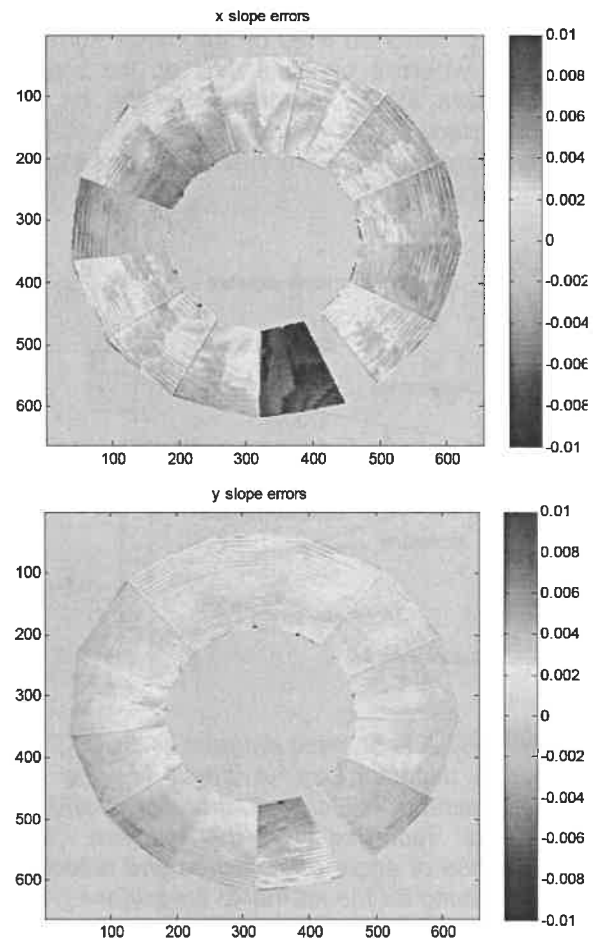


FIGURE 5. X and y slope errors in the solar concentrator. Color bars are 20 mrad. p-v.

Before going on we should point out that there is at least one commercial business using deflectometry for testing the performance of solar concentrators [10].

PRECISION OPTICS TEST

The detail and slope capture range with the solar collector data made us look harder at the limits of the test. If we had slope sensitivity of 10 μ radians over a full radian and spatial resolution of 1000 pixels over the 3 m aperture this would translate to a height sensitivity of less than 10 nm on the solar dish. Could SCOTS be applied to a large optics project where there was difficulty getting good interferometric data at the edge of the steeply aspheric 8.4 m diameter off-axis Giant Magellan Telescope (GMT) mirror being polished at the Steward Observatory Mirror Lab. The numbers made it look like it was worth a try.

The interferometric test used a set of null optics that included a 3.75 m sphere, a 1 m sphere, two computer generated holograms and an instantaneous phase shifting interferometer. Everything but the 4 m sphere was mounted on an optical bench known as Sam. In order to use SCOTS the screen and camera had to be placed above Sam and be able to move out of the way when the interferometer was being used. This meant the circle of least confusion was about 150 mm in diameter and the camera and screen had to be positioned within about 5 mm laterally to avoid vignetting in the 4 m sphere. This alignment had to be done about 20 m over the unprotected GMT mirror. Of course this extra test was taking time away from polishing runs and making life hard for the regular test crew.

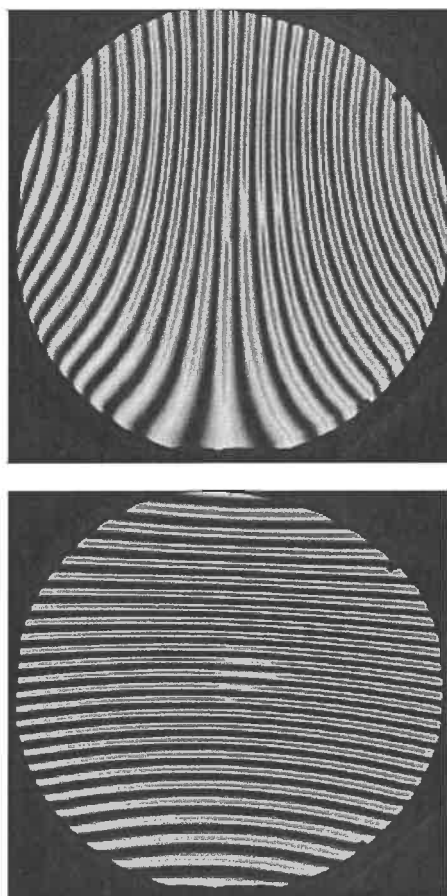


FIGURE 6. Examples of the phase shifting intensity patterns on the GMT mirror in the vertical and horizontal positions.

Once the hardware was properly aligned to see the entire mirror and safely secured line patterns

such as those in Fig. 6 were seen on the GMT mirror.

Of course, these raw data include the power or sag in the mirror as well as the asphericity. Once the theoretical slopes are removed from the data, the slope errors are shown in Fig. 7.

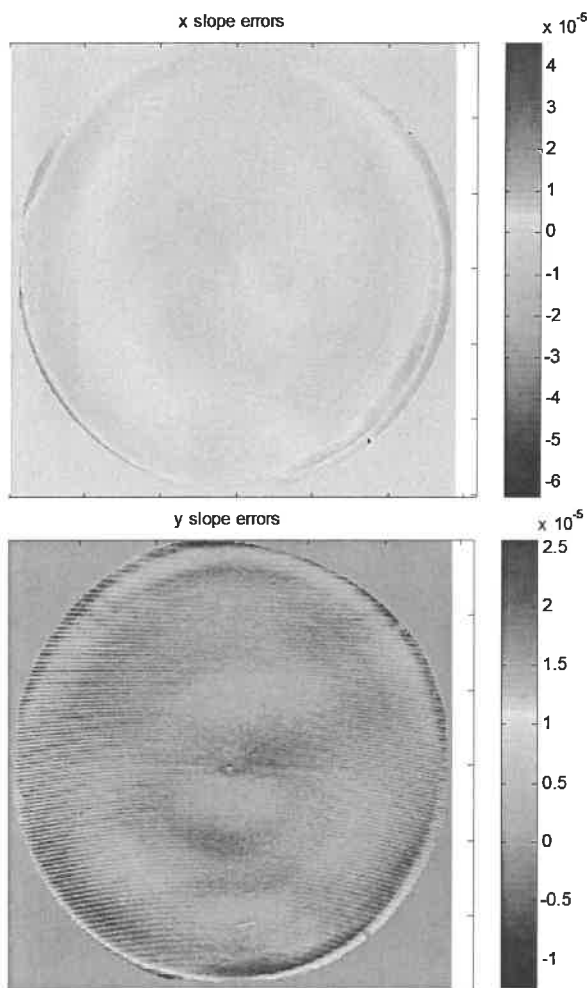


FIGURE 7. The X (110 μ rad. p-v) and Y (38 μ rad. p-v) slope errors based on the data in FIG. 8.

Since the vertex of the parent parabola is over half the diameter of the mirror in the $-y$ direction it is interesting that the largest slope errors are in the x direction and that some of the worst y slopes are where the mirror is most spherical.

Once the slopes are integrated and 24 low order Zernike terms are removed because the final mirror low order figure will be controlled with actuators, the integrated surface height map looks like that in FIG. 8 upper, while the comparable interferometric data with the same

terms removed is shown in FIG. 8 lower. Over the central 90% of the diameter of the aperture the two maps look virtually the same in spatial character and magnitude.

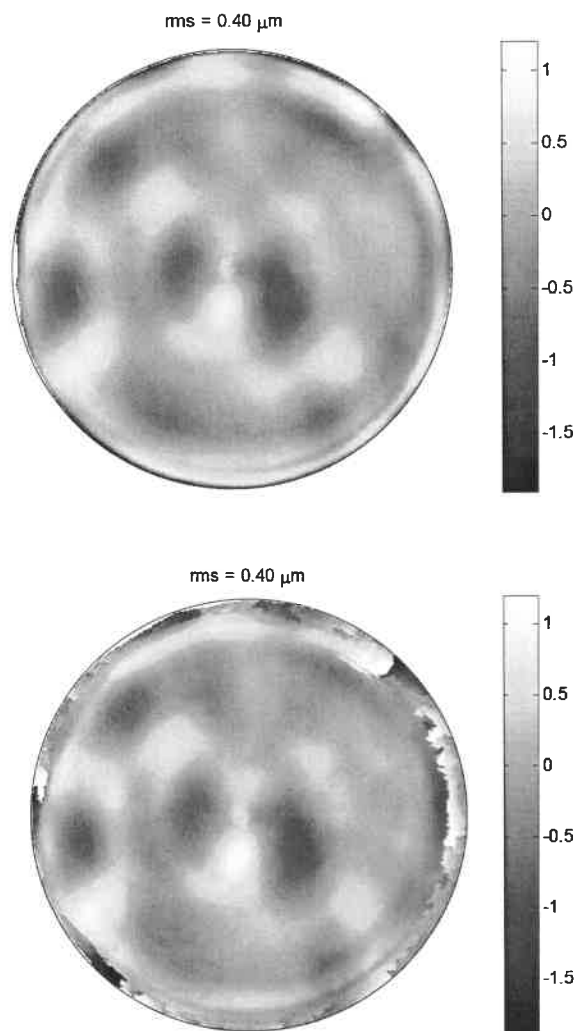


FIGURE 8. The integrated GMT surface data as of 4/22/10 as measured by SCOTS (upper) and direct height measured interferometrically (lower). The circle represents the 8.4 m clear aperture and the color bar units are μm .

At this stage of polishing the GMT team was glad to have the SCOTS data because the slopes were too high at the edge of the mirror to get good interferometric data and this was exactly where work was needed to improve the surface accuracy. The interferometer could not reliably unwrap the direct phase data at the mirror edge.

CONCLUSION

SCOTS provided a path to improve the surface figure of an aspheric mirror with about 14 mm of departure from a sphere where a simultaneous phase shifting interferometer, CGH and one addition null sphere could not give good data. The entire non-null SCOTS test equipment consisted of a 15" LCD computer monitor, a 1024 x 768 pixel, 8 bit digital camera with a fixed focus lens and a laptop computer running Matlab. The first time we tried the test we got useable data over the unvignetted part of the mirror we could see. Getting the test equipment proper positioned above the interferometric test already install took another couple weeks. The test used perhaps \$3000 to \$4000 worth of equipment. Obviously 10 to 100x more time and money that went into the interferometric test.

Based on an apparent angular sensitivity of about 1 μradian and a spatial resolution of about 10 mm, the test has a height resolution of about 10 nm. Nothing has been done to optimize anything about the test and data reduction. We are presently working on methods of removing the effects of lens distortion and alignment, errors that appear in the final result as second order effects rather than first order as in the case of interferometry. Finally it should be recognized that this is an absolute test in the sense there is no reference surface as is an essential part of interferometry.

Our core conclusion, and we are not the first to say this as indicated by some of our references, is that anyone manufacturing interferometers had better be looking over their shoulder. This probably goes more for US manufacturers than others since many people in Europe, and perhaps other regions, seem to understand this already.

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REDUCTION OF NOISE IN INTERFEROMETRIC MEASUREMENTS USING A SYNTHETIC EXTENDED SOURCE

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One of the sources of noise that limits interferometric measurements with a laser source is stray light which can show up as either ghost fringes or speckle. Both of these will print through to the phase data. It is well known that by reducing the coherence of the source it is possible to significantly reduce this source of error. This is done by decreasing the spatial coherence by using an extended source or by decreasing the temporal coherence by using a source with some spectral bandwidth.

Either of these approaches works well in many situations. For our work measuring large, off-axis aspheres, other system requirements drive us to a solution where the standard approaches have significant problems. Our preferred approach for measuring aspheric optics is to use a computer generated hologram (CGH). Because of the wavelength dependence of the imparted phase, we can not use a source with appreciable bandwidth. This means we can not reduce the noise with a short coherence length source. Most of the optics that we make are large, so there is significant air path in our measurements. It also requires great care to build structures that are stiff enough to allow for temporal phase shifting. Because of these two problems, it is desirable to use instantaneous phase shifting. Our preferred approach is to use polarization to accomplish this. This requires the use of two separate, orthogonally polarized sources. If the typical approach of using rotating ground glass is used after the polarization states are separated, the ground glass will not be common and there will be a random phase term added to each pair of point sources. This will result in nothing but speckle. If the ground glass is inserted before the polarization states are separated, all of the polarization optics will not be common path.

In this paper we present an approach for synthetically creating an extended source by averaging multiple measurements together. For each individual measurement, the sources have high spatial coherence, but by moving the

apparent location of the sources between measurements, the average of all of the measurements has the same behavior that one sees from an extended source. The optics that are used to move the source rotate so all non-rotationally symmetrical errors average out. By correctly choosing the placement of these optics, the rotationally symmetrical errors will be nominally common path. This results in an interferometer that uses instantaneous phase shifting, a CGH as a null optic and an extended source for noise reduction.

HIGH-RESOLUTION ABSOLUTE LENGTH AND THICKNESS MEASUREMENTS FROM LARGE STAND-OFF DISTANCES

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INTRODUCTION

Although traditional interferometry can be ideal for displacement metrology, it is often ill-suited for dimensional metrology such as length or thickness measurement due to fringe ambiguities [1]. A number of related technologies compromise the laser's monochromatic nature, and therefore typically the measurement precision, in exchange for the ability to measure over larger windows without ambiguity. These systems rely on large information bandwidths to synthesize full, unambiguous range profiles. For instance, white light or low-coherence interferometry offer very large bandwidths (tens or hundreds of THz) and can be used to profile surface features down to the nanometer level [2,3]. However, the short coherence length typically limits the measurement windows to tens of microns. A reference delay line in these systems can be physically scanned to enable larger effective windows, but this is typically slow, requires continual and precise calibration and monitoring of the reference delay, and is prone to failure due to the physical movement.

Techniques such as OCT and some mode-locked laser techniques aim to retain the large information bandwidths of low-coherence interferometry, which enable high resolution and precision, but they also increase the source coherence in order to increase the measurement window [4]. OCT accomplishes this by linearly sweeping the optical frequency (chirping) relatively narrow-linewidth lasers over large information bandwidths. The improved laser coherence lengths typically allow the measurement windows to reach several millimeters. Again, reference delay lines can be used to create larger effective measurement windows.

At Bridger Photonics, Inc. we have demonstrated dramatic further improvement in the laser coherence compared to OCT, which has led to >100-meter measurement windows, while retaining information bandwidth, and

therefore resolutions and precisions, comparable to low-coherence interferometry and OCT. This allows us to perform precise measurements of length and thickness over very a large range of distances without a scanning delay line. Potential applications include precision dimensional metrology, surface characterization and imaging from large stand-off distances, precision optical component and assembly measurements (thickness and position), and other subfields of industrial metrology.

BACKGROUND AND THEORY

Our technique is similar to OCT in that we chirp a narrow-linewidth laser over large bandwidths (up to 5 THz demonstrated and >15 THz possible with existing laser technology). However, our laser sources are mode-hop-free over the entire sweep, narrower in linewidth, and we perform active laser frequency corrections in order to maintain the linearity of the chirp. These factors enable us to significantly improve the laser coherence, and therefore the measurement window, compared to OCT. In the laser ranging and detection (LADAR) community, our general measurement method is known frequency-modulated continuous-wave (FMCW) LADAR [5].

For FMCW LADAR, one copy of the chirped laser light is transmitted to the target, as shown in Figure 1. The light returning from the target (called the "return" beam) is collected and interferometrically combined with a local reference copy of the chirped light (called the "reference" beam). The combined beam is directed onto a photodetector and an RF beat note results from the time delay between the two combined copies of the chirp at frequency $f_{beat} = \kappa\tau$, where κ is the chirp rate (often in MHz/ μ s), and τ is the time delay between the two chirps. With accurate knowledge of the chirp rate and the beat note frequency, f_{beat} , the time delay can be determined. From the

time delay, the range to target is given simply by $R = \tau c / 2$, where c is the speed of light.

The expected performance of our system can be calculated. We use the definitions adopted by NIST. The range resolution, defined as the minimum resolvable range separation (full width at half maximum) between two targets on the same bearing, is given by $\Delta R = c/2B$, where B is the total bandwidth of the chirp. This equation makes clear the desire for larger bandwidth in order to achieve better resolution. It is only valid over measurement windows that are well within the laser coherence length. The range resolution is a very useful parameter for comparing different systems on equal footing because it does not depend on any details of the transceiver or target, such as transmitted power, target reflectivity, collection aperture, or detector noise.

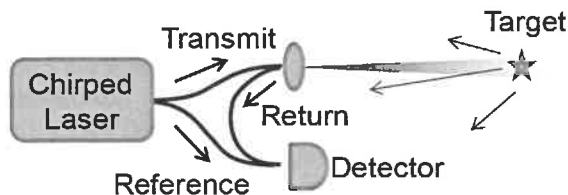


FIGURE 1. Simplified schematic of FMCW LADAR. The reference and return light are combined to generate an RF beat note measured by the detector. The frequency of the beat note indicates the target range.

Conversely, the range precision (also known as the repeatability or reproducibility) depends on the signal-to-noise (SNR) ratio and is defined as the standard deviation of a statistically significant number of range measurements of the same target. Mathematically, a lower limit for the range precision is given by the Cramér-Rao relation $\sigma \approx \Delta R / \sqrt{SNR}$. The measurement precision that a system can achieve can therefore be far better than its resolution. By averaging over multiple measurements the precision can be further improved as $1/\sqrt{N}$, where N is the number of measurements, as long as the noise processes are stochastic. For the system on which we report in this abstract, we used a chirp bandwidth of 3 THz and achieve an SNR of around 70 dB. We therefore expect a resolution of 50 microns and a precision lower limit of 15 nm.

EXPERIMENT AND RESULTS

For this work, we were interested in determining the ability of our system to measure the thickness of a representative optical assembly element (a microscope cover slip). As shown in Figure 2, we placed a nominally 300-micron-thick cover slip at the focus of the laser beam transmitted from our chirped laser beam. The focal length was 200 mm and the difference between our reference path and transmit path to the target was 76.1 cm. We diverted the return light that was reflected from each surface of the cover slip by using a quarter-wave plate and polarizing beam splitter.

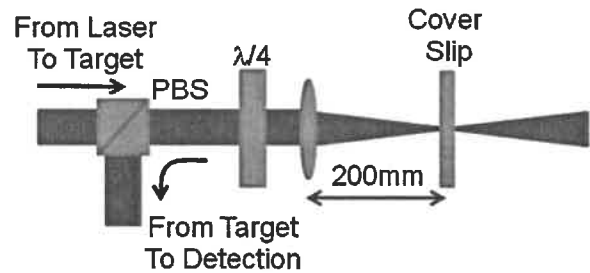


FIGURE 2. Setup used for measuring thickness of cover slip. $\lambda/4$ is a quarter-wave plate and PBS is a polarizing beam splitter. The combination of these two elements allows the reflections from the target to be separated from the transmitted beam to the target.

We then combined the return beam with the reference beam and detected the resulting beat note using a photoreceiver. We digitized the beat note and took the Fourier transform to determine its frequency, which could be converted to range. The resulting range profile is shown in Figure 3 on a logarithmic vertical scale. The signal peak to the noise floor, which was shot-noise-limited, was 76 dB.

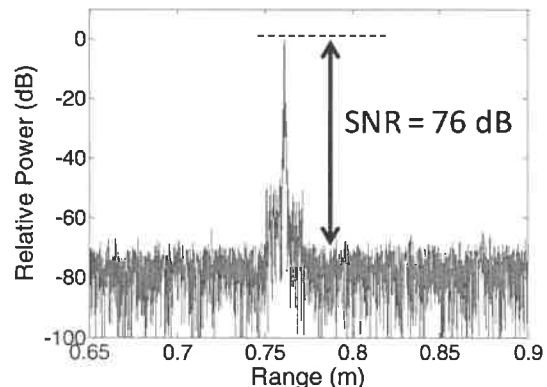


FIGURE 3. Range profile showing the cover slip signal with an SNR of 76 dB.

Figure 4 shows a zoom of the region near the cover slip. From this figure, each surface of the cover slip is easily resolved and the resolution of either peak is measured to be $45\ \mu\text{m}$, as expected. By fitting a Gaussian to each of the peaks that represents each surface, we determined the center range of each surface.

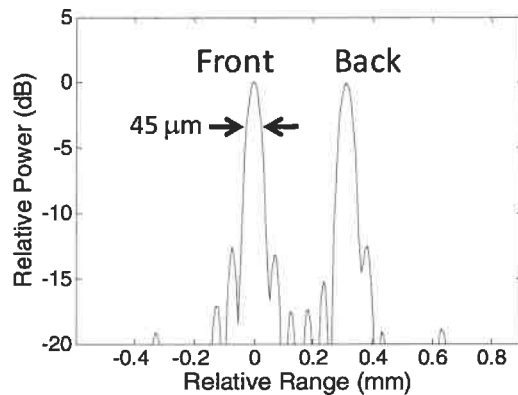


FIGURE 4. Range profile showing the cover slip showing resolved front and back faces. Our measurement resolution is shown to be around 50 microns.

Figure 5 shows the resulting peak centers for the front and back surfaces for 100 successive measurements. The figure also shows the optical thickness of the target, which is obtained by taking the difference between the front and back surface ranges. Due to small drifts in the reference for our laser chirp rate (we did not isolate or stabilize the reference for these measurements), the precision on each surface is around 140 nm. However, because the errors are primarily common to both surfaces, the difference (thickness) can be measured with a precision of 34 nm. This is about a factor of two larger than the Cramér-Rao lower bound, which may be due to residual effects of the reference drift or slight imperfections in the range peaks.

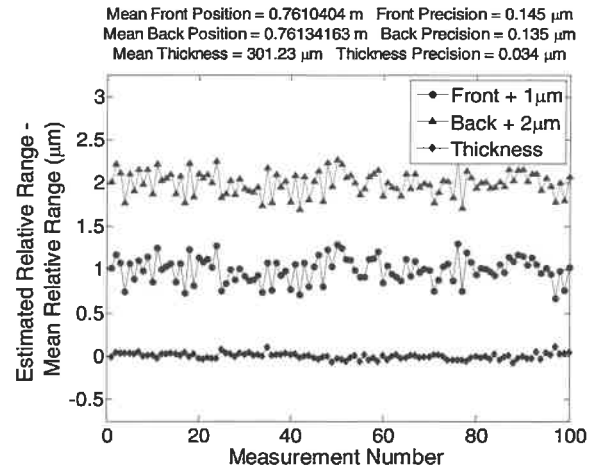


FIGURE 5. Range peak center versus measurement number for the front surface, back surface, and thickness (difference). The measurement precision for the thickness is 34 nm.

We are unaware of other techniques that can measure with such resolution and precision over such a large measurement window. Moreover, if not for atmospheric turbulence, we should be able to perform these measurements over much larger windows (>100 meters).

Although we did not stabilize the reference for our chirp rate for this work, we have done so for other measurements and demonstrated stability of better than 1 part in 10^6 , which should allow us to achieve an accuracy of <300 pm on the thickness of this cover slip.

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FLATNESS MEASUREMENTS OF THIN, PLANE-PARALLEL OPTICS FLOATED ON A HEAVY LIQUID

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INTRODUCTION

The measurement of flatness errors of unconstrained thin parts with low uncertainty is a considerable challenge, because their form is significantly affected by the forces applied through the mechanical fixtures holding them. Forces due to mechanical clamping, chucking in vacuum or electrostatic chucks, and gravity cause surface deformations that must be either eliminated or calibrated.

Absolute tests can sometimes be devised, that permit the separation of instrument errors and mounting-induced errors from the form errors of the part under test. Well known examples are the three-flat tests used for the calibration of interferometer reference flats (see e.g. [1, 2, 3] and the references therein). However, error separation procedures cannot be found for all situations and it is particularly difficult to characterize deformations of a surface due to mounting forces with an absolute test.

We describe a method of separating the intrinsic (or unconstrained) flatness errors of flat precision parts from mounting-induced deformations. Mounting-induced deformations are essentially eliminated when the part is floated on a heavy, high density liquid. The unconstrained flatness error of the part can then be measured directly. The densities of saturated aqueous metatungstate solutions are close to 3 g/cm^3 , which is substantially higher than the densities of many borosilicate crown glasses and important materials with low coefficient of thermal expansion (Table 2), that are used to fabricate precision optics. We illustrate the method with interferometric measurements of the unconstrained flatness errors of silicon and fused silica wafers with a diameter of 300 mm.

An important example of thin, flat optics that must be characterized with very low uncertainty are

photomask substrates and blanks for extreme ultraviolet lithography (EUVL) at a wavelength of 13.5 nm. Photomasks contain the layout of an integrated circuit which is projected, usually demagnified 4:1, onto the wafer surface by an imaging system. EUVL photomask substrates are square with a standard width of 152 mm and a thickness of 6.35 mm. Several low thermal expansion materials (LTEMs) with coefficients of thermal expansion $< 0.03 \times 10^{-6} \text{ K}^{-1}$ are used to make EUVL photomask substrates. Within a quality area of $142 \text{ mm} \times 142 \text{ mm}$, the peak-to-valley flatness error of front- and backsides of an unconstrained EUVL photomask substrate must be as low as 30 nm for the highest quality substrates to achieve the very small pattern placement errors required in EUV lithography. These and other characteristics of EUVL mask substrates are described in a standard published by the Semiconductor Equipment and Materials Industry (SEMI) organization [4]. The method described here was originally developed for measuring the unconstrained flatness error of EUVL photomask blanks and substrates [5].

LITHIUM METATUNGSTATE SOLUTIONS

Lithium metatungstate (LMT), the lithium salt of metatungstic acid with the formula $\text{Li}_6[\text{H}_2\text{W}_{12}\text{O}_{40}] \cdot 3\text{H}_2\text{O}$, is highly soluble in water and other polar solvents [6]. Aqueous solutions of LMT are available commercially for applications requiring separation of materials with different densities, e.g., to separate of fossils from minerals or to separate valuable minerals from sand and clay [7, 8]. Density and viscosity of the tungstate solutions at room temperature depend on the concentration. We chose to use nearly saturated LMT solutions with densities of about 2.95 g/cm^3 . This density is about 30% higher than the density of silica glass and ensures sufficient buoyancy. The properties of the commercially available aqueous LMT solution that are relevant for this application are summarized in Table 1.

TABLE 1. Properties of saturated aqueous lithium metatungstate solutions at room temperature.

Name Abbreviation	Lithium Metatungstate LMT
Formula	$\text{Li}_6[\text{H}_2\text{W}_{12}\text{O}_{40}] \cdot 3\text{H}_2\text{O}$
Density ρ [g/cm ³]	2.95
pH	3.2 ± 0.1
Viscosity μ [mPa·s]	36 ± 1
n (632.8 nm, 16.6 °C)	1.5888 ± 0.0002

Metatungstate solutions are stable only when they are acidic [6] (see Table 1). Many glasses are resistant to corrosion when in contact with an acidic solution, but the corrosion resistance of the materials floated on the solution must be considered before a measurement.

The refractive index of a saturated aqueous LMT solution at 2.95 g/cm³ was measured at 632.8 nm, the wavelength of many phase-shifting interferometers used for form measurements, using the minimum deviation method as described by Burnett and Kaplan [9]. A hollow prism with plane parallel windows was filled with the LMT solution and the deviation angles of light passing through the prism at minimum deviation were measured with a goniometer. Deviation angles were measured for light from a helium-neon laser at 632.834 nm and for the red spectral line emitted by a cadmium-argon low pressure discharge lamp at 643.847 nm. The measurements were made at the laboratory room temperature of 16.6 °C. The refractive index of the saturated LMT solution at 632.8 nm and its standard uncertainty, calculated from the standard deviations of the angle measurements, is 1.5888 ± 0.0002 . Since the index n was measured at two closely spaced wavelengths λ , an estimate for the dispersion near 632.8 nm could also be obtained: $dn/d\lambda = (-7.5 \pm 2.6) \times 10^{-5} \text{ nm}^{-1}$. The refractive index of the saturated LMT solution at 632.8 nm is much higher than the index of water (1.332, see [10]) and even slightly higher than the refractive indices of some glasses. For some materials, especially low thermal expansion materials (see Table 2), the index of the LMT solution can be matched to that of glass by diluting the solution with water.

EXPERIMENTAL SETUP

The wafer flatness was measured with the “eXtremely accurate CALibration InterferometerR”

TABLE 2. Densities and refractive indices at 632.8 nm of several glasses and low thermal expansion materials.

Name	ρ [g/cm ³]	n
Fused silica [11]	2.201	1.4570
Schott BK7 [†]	2.51	1.5151
Schott SF5 [†]	4.06	1.6685
Corning ULE 7972 [†]	2.21	1.4840
Schott ZERODUR [†]	2.55	1.5404
Ohara CLEARCERAM-Z [†]	2.53	1.5477

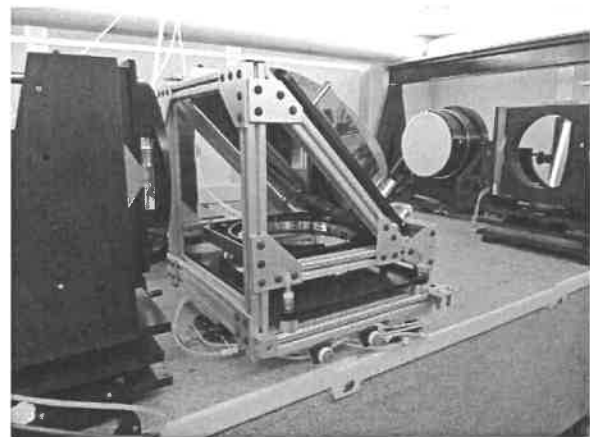


FIGURE 1. Experimental setup using the XCALIBIR interferometer at NIST.

(XCALIBIR) at the National Institute of Standards and Technology (NIST). XCALIBIR is a versatile phase-shifting interferometer operating at a wavelength of 632.8 nm. For the flatness measurements of floating wafers, the interferometer was configured so that the reference flat of the interferometer could be mounted above the photomask in a horizontal orientation. A photograph of the XCALIBIR setup is shown in Fig. 1. The left side of the photograph shows the collimator lens assembly, which creates a collimated test beam of just over 300 mm diameter. The aluminized fold mirror has a diameter of 460 mm and sends the test beam downward to the reference flat, which is visible below the fold mirror in Fig. 1.

A tray machined from an acetal plastic filled with LMT solution was used to float the wafers. Fig. 2 shows a 300 mm diameter silicon wafer floating on a lithium metatungstate solution. In preparation for a flatness measurement, 200 mL of fresh, saturated LMT solution was slowly poured into the tray to avoid the formation of air bubbles and

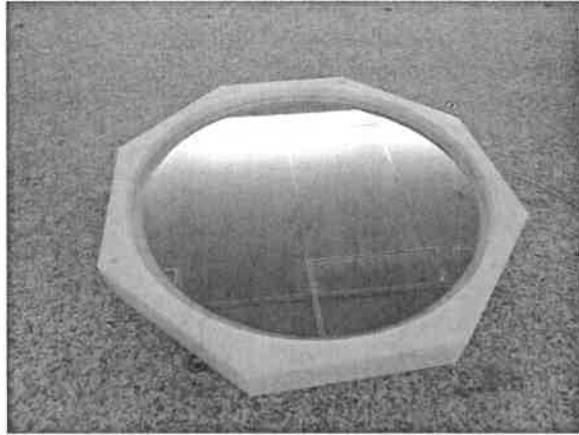


FIGURE 2. A 300 mm diameter silicon wafer floating on a LMT solution.

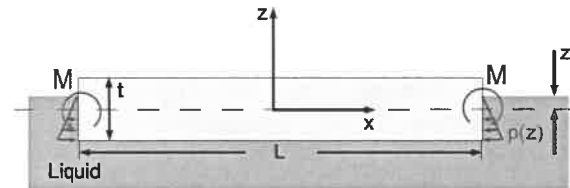


FIGURE 3. Forces and moments acting on a plane-parallel plate floating on a liquid.

the trapping of bubbles at the bottom of the tray. The wafers were then lowered onto the liquid by hand. Three plastic pins were used to prevent lateral movement of the floating parts during measurements. The space between the pins and the wafer is a few tenths of a millimeter to ensure that no force is exerted by the pins on the wafer. Measurements were made immediately after lowering a part onto fresh LMT liquid to avoid problems resulting from water evaporation and crystal formation between the edge of a part and the restraining pins.

While the hydrostatic pressure at the bottom of a floating wafer is constant, a pressure gradient exists at the edges as shown in Fig. 3. The pressure gradient results in a uniformly distributed edge torque M that is balanced by a bending moment of the wafer. The deformation can be calculated analytically for thin plates [12]. The details of the derivation are described in [5].

The equation describing the deformation of a thin plate floating on a liquid by the hydrostatic pres-

sure gradient at the edge is:

$$w(x, y) = \frac{6(1-\nu)g\rho_g}{E} \left(\frac{\rho_g^2}{6\rho_l^2} - \frac{\rho_g}{4\rho_l} \right) (x^2 + y^2), \quad (1)$$

where ρ_g is the density of the glass, ρ_l is the density of the liquid, ν is Poisson's ratio for the glass and E its elastic modulus. The maximum (peak-to-valley) deformation w_m of a square flat with width L is given by:

$$w_m = \frac{3(1-\nu)g\rho_g}{E} \left(\frac{\rho_g}{4\rho_l} - \frac{\rho_g^2}{6\rho_l^2} \right) L^2. \quad (2)$$

Many optical components have a circular shape and it can be shown that the maximum (peak-to-valley) deformation of thin, circular plates with a radius R by hydrostatic pressure gradients at the edge is described by an equation similar to Eq. 1:

$$w_m = \frac{6(1-\nu)g\rho_g}{E} \left(\frac{\rho_g}{4\rho_l} - \frac{\rho_g^2}{6\rho_l^2} \right) R^2. \quad (3)$$

For fused silica $\nu = 0.17$, and $E = 73$ GPa. A fused silica wafer with a 300 mm diameter that is floating on a saturated aqueous LMT solution will have a quadratic deformation of 3.1 nm (peak-valley). Similarly, a silicon wafer with a 300 mm diameter ($\rho = 2.33\text{g/cm}^3$, $\nu = 0.28$, $E = 185$ GPa) has a deformation of 1.1 nm due to the hydrostatic pressure gradient at the wafer edge.

WAFER FLATNESS MEASUREMENTS

Fig. 4 shows the unconstrained flatness error of an early 300 mm diameter silicon wafer. The wafer shows the characteristic waviness of a wafer that was cut from a silicon boule using a linear wire saw. The wafer in Fig. 5 is made from silica glass and polished with conventional optical polishing methods. The refractive index of the LMT solution was higher than the index of silica glass and the reflection from the back surface of the wafer was attenuated, but not completely eliminated. The attenuation of the unwanted reflection was found to be sufficient for a flatness error measurement of the wafer front surface.

CONCLUSIONS

The flatness error of thin, flexible plane-parallel parts can be measured with low uncertainty when they are floated on a LMT solution, because the part is supported by a uniform pressure that does not distort the shape. The density of saturated lithium metatungstate solutions is sufficiently high

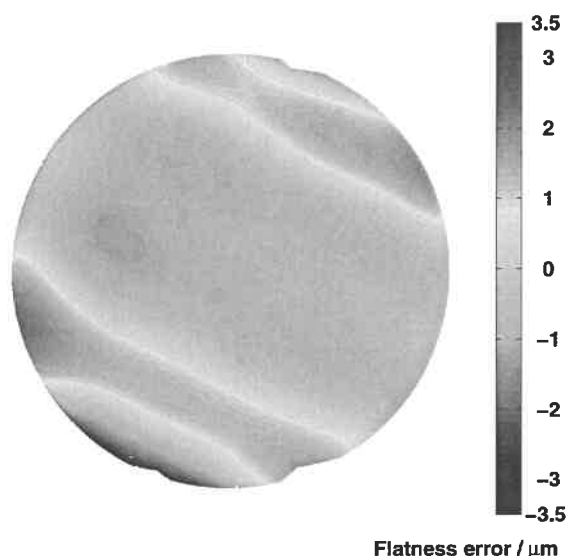


FIGURE 4. Unconstrained flatness error of a 300 mm diameter silicon wafer floating on a LMT solution.

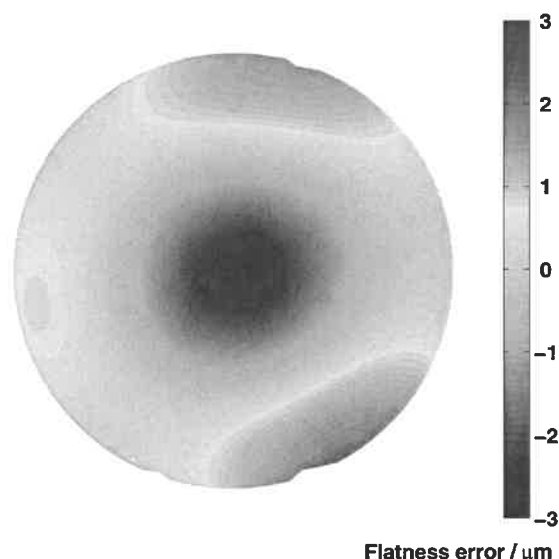


FIGURE 5. Flatness error of a 300 mm diameter silica glass wafer floating on a LMT solution.

to permit lower density glasses to be floated on the heavy liquid. Several important materials with ultra-low thermal expansion can also be floated on LMT solutions. A small quadratic form error results from the hydrostatic pressure gradient at the edge of a floating plate, which leads to a bending moment. The plate bending can be predicted with an analytical model.

†Disclaimer: The full description of the procedures used in this paper requires the identification of certain commercial products and their suppliers. The inclusion of such information should in no way be construed as indicating that such products or suppliers are endorsed by NIST or are recommended by NIST or that they are necessarily the best materials or suppliers for the purposes described.

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LIGO - A LOOK BEHIND ATTOMETER (10^{-18} m) SENSITIVITY AND BEYOND

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INTRODUCTION

The Laser Interferometer Gravitational-wave Observatory (LIGO)[1,2], consisting of three interferometers at the two LIGO observatory sites (Livingston, LA and Hanford, WA) is operated by the LIGO Scientific Collaboration (LSC). The LSC currently consists of approximately 760 members from various institutions worldwide.

Each LIGO detector is a power-recycled Michelson Interferometer with Fabry-Perot cavities in the 4 km long arms. We discuss the operation of the LIGO interferometers, and the techniques that were used to reach a sensitivity of better than 10^{-18} m/Hz^{-1/2} for signals around 100 Hz. In the second part we discuss how the next generation Advanced LIGO (aLIGO)[3,4] will achieve even greater sensitivity.

GRAVITATIONAL WAVES

To motivate the required extremely high sensitivity to length changes, the following section will give a brief idea about what gravitational waves are and how to detect them. Gravitational waves (GW) were predicted by Einstein in 1916 [5] as propagating fluctuations in the curvature of space-time. They are emissions from accelerating non-spherical mass distributions.

Gravitational waves travel at the speed of light and are quadrupolar distortions of distances between freely falling masses. Their amplitude is measured in "strain", as defined in equation (1):

$$h = \frac{\Delta L}{L}. \quad (1)$$

The predicted amplitude, approximated for binary neutron star systems is shown in equation (2):

$$h \approx \frac{4\pi^2 G M R^2 f_{orb}^2}{c^4 r}. \quad (2)$$

This yields an expected amplitude of a gravitational wave originating from a binary neutron star system in the Virgo cluster to $h = \Delta L/L \approx 10^{-21}$ or approximately $4 \cdot 10^{-18}$ m. This effect of a gravitational wave on Michelson type

interferometer is symbolized (hugely exaggerated) in figure 1.

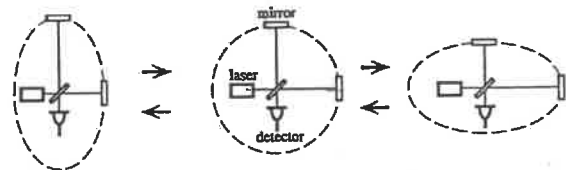


FIGURE 1: Changes of the differential arm length are measurable with a Michelson interferometer.

LIGO DETECTOR

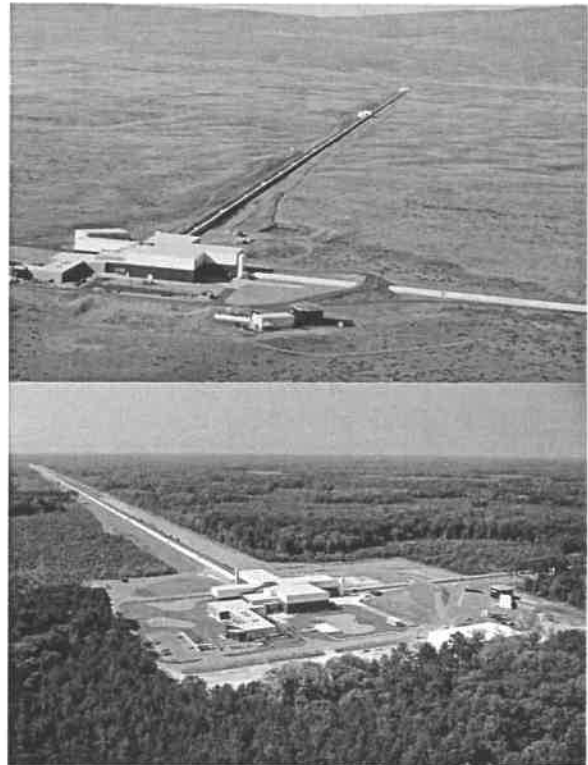


FIGURE 2: Top: The LIGO site in Hanford, WA. Bottom: The LIGO detector site in Livingston, LA.

LIGO is a Michelson interferometer with some extras to increase the sensitivity and suppress the unwanted noise from the environment. The

detectors are described in greater detail in [2]. Figure 2 shows the two detector sites with the housings for the two interferometers with 4 km long arms (Called H1 and L1). The observatories have a support infrastructure of clean rooms, preparation laboratories, maintenance shops, and computer networking for control, data acquisition and analysis. In LIGO all optical elements, and the laser beam between them, operate in UHV. The basic optical configuration of each LIGO detector is that of a power-recycled Michelson interferometer with resonant arm cavities as shown in figure 3:

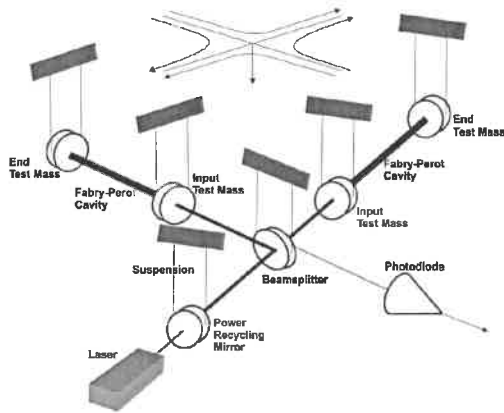


FIGURE 3: Schematic view of the interferometer with Fabry-Perot arm cavities and Power-recycling.

The power-recycling mirror forms a resonant optical cavity with the interferometer, causing a build-up of power in the recycling cavity and hereby acting as if a more powerful laser would have been used in front of the interferometer.

The input test masses together with the end mirrors form a cavity that acts as a means to increase the storage time of the light in each interferometer arm, effectively increasing the arm lengths (and improving the strain sensitivity) by ~100 times.

To decouple the environment from the position of the test masses all mirrors are freely suspended as a pendulum from vibration-isolated platforms to attenuate external disturbances in the gravitational wave band

ADVANCED LIGO

While the LIGO interferometers are currently running Advanced LIGO is about to be realized. Its goal is to improve the sensitivity by more than a factor of 10 beyond initial LIGO. This new detector will replace the present detector but

reuse the vacuum envelope of the observatory sites. The new instruments take advantage of research that has taken place since the initial instruments were designed in the mid-1990s. Improved are the lasers (180 W highly-stabilized systems), optics (40 kg fused silica test masses), seismic isolation systems (using inertial sensing and feedback), and the readout of the interferometer.

Advanced LIGO was approved by the National Science Board in October 2004, and the project started with funding in April 2008. The current LIGO will go offline in 2011 and after the installation and commissioning phase it is planned to start observations with aLIGO in 2015.

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AN ANALYTICAL DESCRIPTION OF LOW FINESSE, OPTICAL FIBER FABRY-PEROT INTERFEROMETERS INCORPORATING MULTIPLE REFLECTIONS AND ANGULAR MISALIGNMENT

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Despite the widespread use of the external cavity fiber Fabry-Perot interferometer (EFPI) as a displacement sensor and the more than two decades since its invention, an accurate analytical description of the optics unique to the EFPI has been absent from the literature. Using the Gaussian beam approximation for the guided mode of a single mode fiber, we describe the optics of the EFPI including multiple reflections and angular misalignments. The description of uncoated optical fibers aligned against highly reflective surfaces makes a number of predictions including attenuation of the peak-to-peak interference as the cavity length approaches zero, asymmetric fringes in the presence of perfectly lossless mirrors, and increased displacement sensitivity on misalignment. The predictions of the model are confirmed by a series of experiments in which EFPI cavities are formed between uncoated optical fibers and a set of mirrors of varying reflectivity. The cavity lengths are swept, and the predicted interferograms are found to be in good agreement with experimental results across the entire parameter space.

In a sealed chamber, the air refractive index can be assumed as a function of pressure (p) and temperature (T), $n_{air} = n(p, T)$. Therefore, Δn_{air} is calculated from the pressure and temperature changes Δp , ΔT by the following equation

$$\Delta n_{air} = \frac{\partial n_{air}}{\partial p} \Delta p + \frac{\partial n_{air}}{\partial T} \Delta T \quad (1).$$

Since the temperature is kept constant within 10 mK, the air refractive index must be changed according to the pressure change. Beside that, the relationship between the pressure and chamber's volume can be explained by the ideal gas law as following equations with an assumption of no air leakage from inside to outside

$$pV = mRT \quad (2),$$

or

$$\frac{\Delta p}{p} = -\frac{\Delta V}{V} + \frac{\Delta T}{T} \quad (3),$$

where V , m and R are the chamber volume, a number of moles of air and an ideal gas constant, respectively. Δp , ΔV and ΔT are shifts of p , V , T , respectively. From equation (1) and (3), we obtain

$$\Delta n_{air} = -\frac{\partial n_{air}}{\partial p} p \frac{\Delta V}{V} + \left(\frac{\partial n_{air}}{\partial p} p \frac{1}{T} + \frac{\partial n_{air}}{\partial T} \right) \Delta T \quad (4).$$

In the region of 633 nm, $\partial n_{air}/\partial p$ and $\partial n_{air}/\partial T$ are approximately of $2.7 \times 10^{-9} \text{ Pa}^{-1}$, $-9.4 \times 10^{-7} \text{ K}^{-1}$, respectively [8]. If the nominal temperature (T), pressure (p) and temperature change (ΔT) are 296 K, 101.3 kPa and 10 mK, respectively, then Δn_{air} owing to ΔT can be neglected. Therefore, we can compensate Δn_{air} by adjusting the volume ΔV of the chamber. A volume actuator, driven by a controllable PZT actuator, is connected to the bellows to adjust the volume of the chamber.

In order to control the volume of the chamber properly, the Δn_{air} needs to be observed precisely. In the system, a FPC utilized with an ULTEM is used as a Δn_{air} sensor, which can detect Δn_{air} at resolution of 10^{-9} order or less [4]. In figure 1, a laser beam from a frequency stabilized laser (FSL) is phase modulated by an electro optical modulator (EOM) at modulation frequency (ω_m). Then, the beam is fed into chamber via a single mode fiber (SM) and a fiber-through connector. The laser beam output

of the SM is collimated, and then incidents to the FPC after passing a mode matching lens, steering mirrors (SMs), a polarization beam splitter (PBS) and quarter wave plate ($\lambda/4$), respectively. The reflection from the cavity is back to $\lambda/4$ plate, PBS and then, it passes to a pin-hole, which acts as a spatial filter to accept only one laser mode to reach to an avalanche photo-detector (APD) via a multimode fiber (MM) and a fiber-through connector. The signal from APD is sent to a lock-in amplifier (LIA) for synchronous phase detection with the modulation signal applied to the EOM. At the resonance of the FPC, the LIA signal must be null [3], we obtain

$$n_{air} L = \frac{cN}{2f} \quad (5),$$

where n_{air} , f , L , N and c are the air-refractive-index, the center frequency of the ECLD, the cavity length, the interference specific fringe order and the speed of light in vacuum, respectively. Δn_{air} can be derived from

$$\frac{\Delta n_{air}}{n_{air}} = -\frac{\Delta f}{f} - \frac{\Delta L}{L} + \frac{\Delta N}{N} \quad (6),$$

where Δn_{air} , Δf , ΔL , and ΔN are the shifts of n_{air} , f , L and N , respectively. Under the conditions of thermal expansion coefficient of the ULTEM $\alpha = 2 \times 10^{-8}/\text{K}$, $\Delta T \leq 10 \text{ mK}$ (or $\Delta L/L \leq 10^{-10}$) and $\Delta f/f \leq 2 \times 10^{-9}$, the ratio $\Delta n_{air}/n_{air}$ can be calculated using the next equation with the estimated uncertainty of 10^{-9} -order or less

$$\frac{\Delta n_{air}}{n_{air}} \approx \frac{\Delta N}{N} \quad (7).$$

When the air refractive index inside chamber is changed, the off-resonance of the FPC is occurred. It makes the LIA signal is not a null value. A DSP (a proportional-integral-derivative controller with the analogue to digital and digital to analogue converters) uses the LIA signal to generate a compensation signal for controlling the chamber volume actuator to maintain the resonance state of the FPC (means to keep some specific interference fringe order). Therefore, the air refractive index can be stabilized.

INSTRUMENTATIONS AND EXPERIMENTAL RESULTS

Two experiments are performed for the construction of the chamber. The first experiment is to confirm that the PZT actuator, as chamber volume actuator, is available for the

[illegible]

MM fiber receptacle

MM from chamber

APD

LIA

PC&DSP

ECLD

FI

BS

FI

FSL

SM fiber coupler

OSC

ω_m

EOM

$\lambda/2$

PBS

PL

HSPD

FC

Data acquisition PC

SM

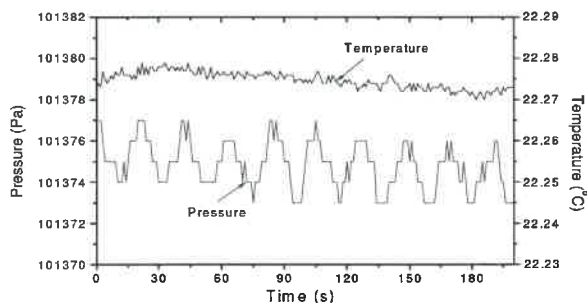
Go to chamber

FIGURE 2. Δn_{air} measurement system using frequency change method. a) Chamber configuration, b) laser sources and optical configuration

An external cavity laser diode (ECLD) is used instead of the FSL (in figure 1) as the light source for the FPC, which was described above, in section 2. The laser beam from ECLD (New Focus, Velocity 6304, 633 nm, linewidth ~500 kHz) is phase modulated by the EOM (New

$$\frac{\Delta n_{air}}{n_{air}} \approx \frac{\Delta f}{f} \quad (8).$$

The PZT actuator is driven by a triangle signal (90 Vpp, 0.05 Hz) via a function generator (FG) and an amplifier (Amp). This signal causes the inner pressure change ~ 4 Pa. Figure 3 shows a plot of temperature and pressure changes while moving the bellows. It can be seen that the inner pressure is changed owing to the motion of the bellows. The Δn_{air} is measured by frequency method and compared with Ciddor method, which calculates the Δn_{air} using pressure, temperature and humidity sensors. Comparison between these methods and the lock-in signal of frequency method is shown in figure 4. The cross correlation ratio of these two methods is estimated of 0.88. It shows a good agreement of Δn_{air} measurement compared with the numerical method given by Ciddor. The lock-in signal of the frequency method is null during the measurement time. It means that the air refractive index is locked to some specific resonances of the FPC and these resonances are maintained by controlling ECLD frequency. The experimental result confirms that the PZT actuator can be used to for the construction of the constant “air refractive index” chamber



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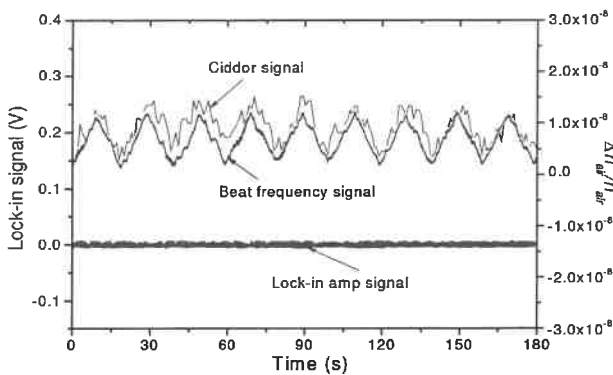


FIGURE 4. Comparison of two Δn_{air} measurement methods: laser frequency with lock-in signal and the Ciddor methods

The second experiment is to stabilize air refractive index inside the chamber using PZT volume actuator. In this experiment, the light source of the FPC is the FSL (Spectra Physics, 1117A, linewidth ~ 1 MHz), and the air refractive index is locked to some specific resonances of the FPC. The resonances are maintained by controlling PZT actuator (means controlling the inner pressure). The stability of air refractive index is evaluated by two conventional methods: the first one uses the Wavelength Tracker [3] and the second uses the Ciddor method [4]. Figure 5 shows the measurement of Δn_{air} in the chamber when the bellows is not controlled. It can be seen that, during the measurement time of ~ 100 s, the air-refractive-index inside the chamber is changed about 3×10^{-8} -order. It is expected that if the compensation process is activated, this level must be reduced.

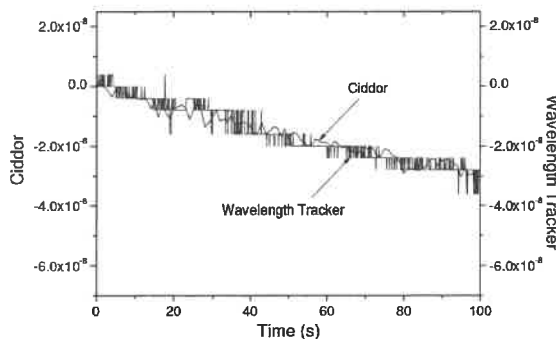


FIGURE 5. Δn_{air} measurement by the Ciddor method and the Wavelength Tracker, taken when the bellow is not controlled

The results of Δn_{air} measurement when the control system is activated and the temperature,

controlled pressured are shown in figure 6 and figure 7, respectively. According to the controlled pressure (~ 6 Pa), it is understood that the level of the air-refractive-index change is supposed to change of $\sim 1.6 \times 10^{-8}$ -order and the adjustment of the pressure can compensate and keep the air-refractive-index change (time variation) within 4×10^{-9} -order, equal to the limitation of the evaluation method. Moreover, the LIA signal (also shown in figure 6) is null during the measurement time. It means that, by controlling the volume actuator, the air refractive index can be locked to some specific resonances of the FPC. From the experimental results, it is concludes that the air refractive index inside the chamber can be kept to be constant using the combination of the FSL, the FPC supported on the ULTEM and the bellows actuator.

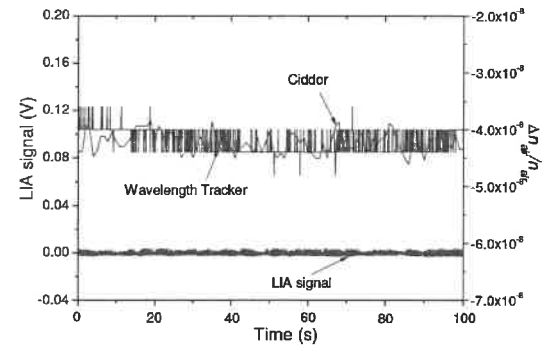


FIGURE 6. Evaluation of stabilization of Δn_{air} from the Wavelength Tracker and the Ciddor method when control system is activated

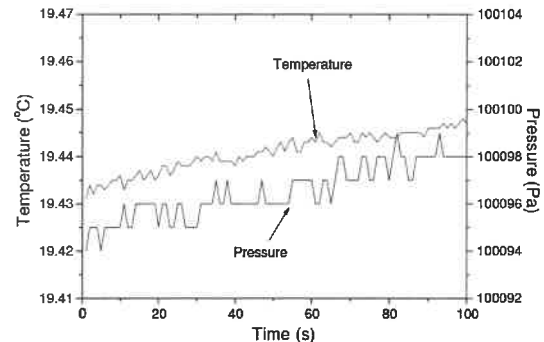


FIGURE 7. Temperature and controlled pressure during Δn_{air} suppression time.

The measurement (or control) uncertainty of our proposed method is evaluated from the sum of the uncertainty of all items that appeared in equation (6), including laser frequency fluctuation, deformation of the optical path length

and the control quality, respectively. The total uncertainty can be estimated by

$$U_{\Delta n_{air}/n_{air}} = \sqrt{\{U_{\Delta f/f}\}^2 + \{U_{\Delta L/L}\}^2 + \{U_{\Delta N/N}\}^2} \quad (9).$$

The short term instability of the FSL is 1 MHz, equivalent to the uncertainty of $\Delta f/f$: $U_{\Delta f/f} \approx 2 \times 10^{-9}$ order. The deformation of the optical path length depends on the temperature and pressure change, respectively. During the measurement time, temperature change is of ~ 16 mK, pressure change is of 4 Pa, causing the uncertainty $U_{\Delta L/L} \approx 3.2 \times 10^{-10}$ order. The uncertainty from the control quality of the system depends on the signal-to-noise (S/N) of the system, including the noise from PZT controller and the noise of the lock-in signal. From the experimental data, this uncertainty is estimated of: $U_{\Delta N/N} \approx 2.8 \times 10^{-11}$ order. Therefore, the frequency fluctuation is the biggest uncertainty factor in this experiment. When another FSL, such as an Iodine-frequency stabilized He-Ne laser is used instead of the FSL of this experiment, the measurement uncertainty can be improved. Table 1 shows the total uncertainty of the system.

TABLE 1. Uncertainties estimation of the Δn_{air} suppression system

Uncertainties	$U_{\Delta f/f}$	$U_{\Delta L/L}$	$U_{\Delta N/N}$	Total
	2×10^{-9}	3.2×10^{-10}	2.8×10^{-11}	2.1×10^{-9}

CONCLUSIONS

The constant “air-refractive-index” chamber using the combination of the FPC, the ULTEM, the FSL and the PZT volume actuator was constructed. The air-refractive-index fluctuation inside the chamber was actively suppressed with the uncertainty of 10^{-9} -order. Therefore, this chamber is adequate for the precision interferometry systems that require resolution of nanometer order. At the current time, our proposed chamber is valid for only short measurement time (~ 100 s) due to the limitation of the frequency stability of the FSL. In the near future, the improvement of the measurement uncertainty to 10^{-10} -order or less will be performed using the Iodine-frequency stabilized

He-Ne laser with frequency stability of $\sim 2.5 \times 10^{-11}$ order. In addition, the other evaluation method to monitor the air-refractive-index, whose resolution is of 10^{-10} -order or less, will be used to confirm the stabilization of air-refractive-index in the chamber. The spatial distribution of the air-refractive-index in the chamber will also be investigated in the near future.

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A LINEAR MODEL OF FRINGE GENERATION AND ANALYSIS IN COHERENCE SCANNING INTERFEROMETRY

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INTRODUCTION

Coherence scanning interferometry (CSI) or scanning white light interferometry (SWLI) as it is often called is an increasingly popular method to characterize engineering surfaces. Combining the lateral resolution of a high power optical microscope with the axial resolution of an interferometer, CSI often provides a more rapid and more convenient means to measure surface topography than the contacting methods that form the basis of current international standards for surface measurement. Routine use of CSI for engineering metrology has, however, prompted comparison with traditional stylus profilometry. In 1990 Hillman was the first to report that CSI measurements of a roughness standard could differ significantly from those obtained from stylus profilometry [1]. Other observations include so-called 'batwings' that are found at the edge of step discontinuities [2] and 'fringe order' errors that occur at half-multiples of the wavelength [3]. For example, figure 1 shows a CSI measurement of a metalized sinusoidal grating.

occur when the surface gradient is large and consequently less of the scattered field is collected by the aperture of the objective. Nevertheless, large surface gradients are encountered when measuring rough engineering surfaces and for this reason the origins of the error sources deserve further consideration.

In a recent paper we have compared three-dimensional (3D) imaging systems including holography, confocal microscopy and CSI as linear processes [5]. This analysis is strictly correct for the case of weakly scattering objects where the object causes a small perturbation in the illuminating field. In this way each system is characterized in the space domain by its point spread function (PSF) (its response to a point object) or equivalently in the frequency domain by its transfer function, and the imaging process can be considered to be a 3D filtering operation. In most practical cases of imaging through 3D transparent media the assumption of weak scattering is rarely satisfied due to relatively large refractive index changes. For CSI

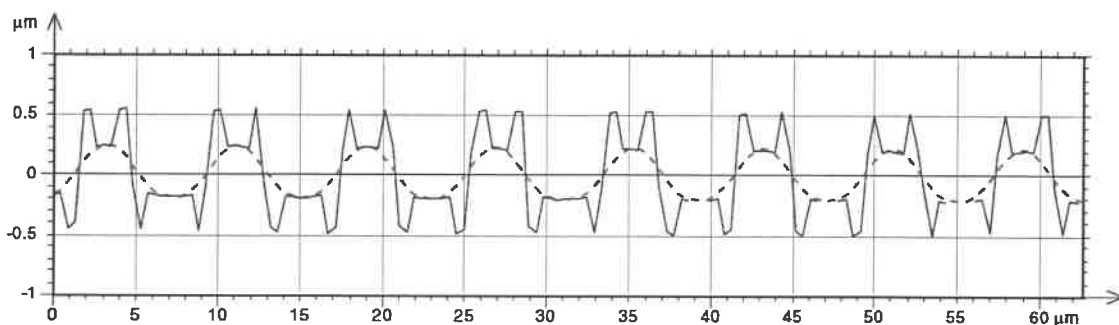


FIGURE 1. CSI measurement of sinusoidal grating 8 μm pitch, 466 nm amplitude (pk-pk). The ideal form is shown by the dashed line. The figure clearly shows fringe order errors of 300 nm.

Although different models of CSI instruments differ significantly in the manner in which they estimate surface profile from the measured interferogram, they share similar optical geometries and errors of this kind are observed in all commercial instruments [4]. It should be emphasized that spurious data is most likely to

measurements of surface profile, however, the assumption of weak scattering can be justified provided the field is returned to the instrument by a single scattering. In this case the linear imaging theory provides considerable insight into the behaviour of CSI measurements. In this paper the origin of gradient induced fringe order

errors is examined using linear systems theory. A new 'foil model' of CSI is introduced that illustrates the formation of white light interference fringes and the model is used to show how the PSF influences fringe order errors. The paper describes how to calculate the PSF for ideal instruments and those that exhibit axial aberration such as defocus and axial chromatic aberration.

LINEAR IMAGING THEORY

We have recently published an analysis of 3D optical imaging methods, including CSI, in terms of linear systems theory [5]. It is shown that, if the object is described by its refractive index contrast,

$$\Delta(\mathbf{r}) = 1 - n^2(\mathbf{r}) \quad (1)$$

where, $n(\mathbf{r})$ is the refractive index, then the fringe modulation, $I(\mathbf{r})$, of the interference pattern generated by a CSI instrument can be described by the linear, shift-invariant filtering operation,

$$I(\mathbf{r}) = \int_{-\infty}^{+\infty} H(\mathbf{r} - \mathbf{r}') \Delta(\mathbf{r}') d^3\mathbf{r}' \quad (2)$$

where $d^3\mathbf{r}'$ represents the scalar $dr'_x dr'_y dr'_z$, and $H(\mathbf{r})$ is the 3D PSF that defines the system response.

In essence, the PSF of a CSI instrument is a function of the 3D coherent responses of the optical systems used to both illuminate and observe the light that is scattered from the object. The 3D coherent response, $G(\mathbf{r}, k_0)$, of an ideal imaging system with a numerical aperture N_A , operating at wavenumber k_0 can be written in the form [5],

$$G(\mathbf{r}, k_0) = \int_{-\infty}^{+\infty} \frac{\delta(|\mathbf{k}| - k_0)}{k_0^2} \text{step}(\mathbf{k} \cdot \hat{\mathbf{o}} - k_0 \sqrt{1 - N_A^2}) e^{i\mathbf{k} \cdot \mathbf{r}} d^3\mathbf{k} \quad (3)$$

where, $\hat{\mathbf{o}}$ is a unit vector in the direction of the optical axis and $\delta(\)$ and $\text{step}(\)$ represent a 3D Dirac delta function and a Heaviside step function, respectively.

Most CSI instruments use a Mirau objective for high resolution measurements and the numerical aperture of this lens usually limits the response of both the illumination and

observation functions. In this case the PSF of an ideal aberration free instrument system has been shown to be [5],

$$H_{\text{ideal}}(\mathbf{r}) = \text{Re} \left\{ \int_{-\infty}^{+\infty} k_0^2 S(k_0) G^2(\mathbf{r}, k_0) dk_0 \right\} \quad (4)$$

where, $\text{Re}\{ \}$ denotes the real part and $S(k_0)$ is the spectral density of the illumination. For the purposes of this paper, however, it is useful to differentiate between the responses $G_i(\mathbf{r}, k_0)$ and $G_o(\mathbf{r}, k_0)$ of the illumination and observation optics respectively, such that, the more general PSF can be written

$$H(\mathbf{r}) = \text{Re} \left\{ \int_{-\infty}^{+\infty} k_0^2 S(k_0) G_i(\mathbf{r}, k_0) G_o(\mathbf{r}, k_0) dk_0 \right\} \quad (5)$$

In essence the PSF provides the interferogram that would be observed if a point-like object were measured by a CSI instrument.

Figure 2 shows a slice through the PSF of an ideal instrument of $N_A = 0.55$ with a Gaussian distributed spectral density such that the central wavelength is 600 nm and the bandwidth approximately 135 nm (at $1/e^2$).

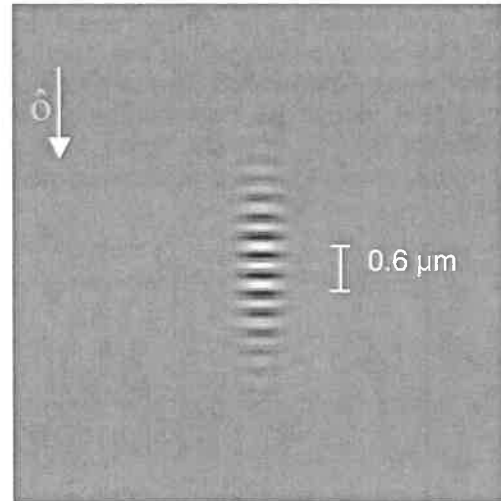


FIGURE 2. Ideal PSF ($N_A = 0.55$; mean wavelength 0.6 μm ; bandwidth 135 nm).

It can be seen that the PSF has a fairly compact form with fringes with a frequency of approximately half the mean wavelength extending in the axial direction. The lateral extent of the fringes (full width) is around 0.6 μm and is approximately the mean wavelength for this objective. It is noted, however, that the PSF extends to a certain extent beyond this limit and

this implies that the fringe pattern generated by a CSI instrument at a particular position in space depends in part on the profile of the surrounding area.

THE FOIL MODEL

Aside from the assumption of scalar diffraction, the linear theory of CSI rests, fundamentally, on the assumption of weak scattering. Weak scattering from an inhomogeneous 3D object occurs when the illuminating field is largely unperturbed by the object itself [6]. This is the case, for example, if a homogeneous medium is sparsely seeded with small particles that scatter only a small fraction of the illuminating field. In this case the fringe pattern observed at each particle location would take a form similar to figure 2.

For more general inhomogeneous 3D objects, weak scattering can rarely be justified. This is because the wavelength of the field within an inhomogeneous bulk material generally varies significantly and after a propagation of just a few wavelengths the phase of the internal field will depart significantly from the illuminating field. In optical profilometry, however, the situation is significantly different since we are generally concerned with scattering from the surface of a homogeneous media. In this case, the assumption of weak scattering implies that the illuminating field at the surface is that which would be present in the absence of the object. In effect, this means that the scattered field propagates from the surface via a single scattering event. Multiple scattering will occur predominantly when attempting to measure rough or high aspect ratio surfaces [7], however, for the smooth surfaces that are the subject of this paper, it can be neglected.

Because we are concerned with surface scattering it is intuitive to consider only a thin 'foil-like' layer on the object surface. Indeed, for the case of a metal object, the illuminating field is rapidly attenuated and is only of significance within the skin depth [6] and the remainder of the object has no measurable effect. If the metal is a perfect conductor then the skin depth is infinitesimally small while the (complex) refractive index contrast is infinitely large and the scattered field will be exactly that which would be scattered from a thin foil with the same profile. In this case we can describe the object by an equivalent foil surface and can write,

$$I(\mathbf{r}) = \int_{-\infty}^{+\infty} H(\mathbf{r} - \mathbf{r}') \delta(r'_x) \delta(r'_y) \delta(r'_z - f(r'_x, r'_y)) d^3 r' \quad (6)$$

where, $f(r'_x, r'_y)$ describes the profile. Here, we have assumed, without loss of generality, the observation direction is aligned to z-axis. We will refer to this equation as the foil model of CSI.

Although we have introduced the foil model with reference to a perfect conductor, it can be used with some validity to model surface scattering from most homogeneous engineering materials. In a real metal, for example, the inhomogeneous field within the skin depth affects the phase and amplitude of the scattered field and because of this the reflection coefficient varies as a function of the angle of incidence, and is polarization dependent [6]. For the case of CSI, however, the variation is small for the range of angles accepted by the numerical aperture of a typical instrument and the phase change results in an apparent movement of the object surface in an axial direction. For the case of a dielectric surface, the situation is similar, however, there is no phase change and although the magnitude of the reflection coefficient is relatively small it is reasonably constant over the range of angles accepted by the N_A of the instrument. Consequently, provided that there is no multiple scattering from internal surfaces (such as thick films), scattering from dielectric and metal surfaces will closely resemble that from a perfect conductor and the foil model will remain valid.

To illustrate the fringe generation process and the effect of the PSF we now consider the fringes obtained when a sinusoidal surface form is investigated using an ideal CSI instrument that is free from aberration. The sinusoidal profile is modelled as the foil defined by the profile,

$$f(r'_x, r'_y) = A \sin(2\pi r'_x / \lambda_g) \quad (7)$$

where, A and λ_g are the amplitude and wavelength of the grating respectively. In this work the 3D convolution of equation (2) was evaluated numerically using an FFT algorithm implemented in MATLAB software. To avoid errors introduced by the discrete numerical formulation it is necessary to ensure that both the foil model and the PSF are adequately sampled. For the case of the foil model this was

accomplished by introducing a Gaussian thickness profile such that,

$$\delta(r_z - f(r_x, r_y)) \approx \exp\left(-2\left(\frac{r_z - f(r_x, r_y)}{T}\right)^2\right) \quad (8)$$

where T is the thickness (at $1/e^2$) point and was chosen to be approximately quarter of the mean wavelength. Figure 3 shows the interferogram generated by the foil model of CSI for the case of the ideal system specified previously when the instrument is used to measure a grating with the same pitch and amplitude as that illustrated in figure 1.

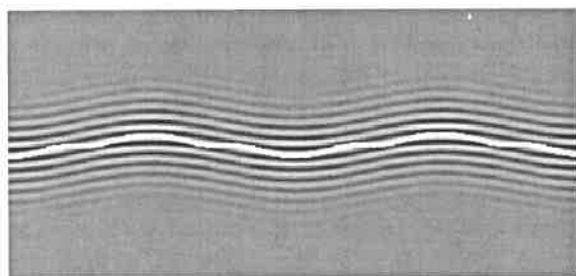


FIGURE 3. Interferogram generated by the foil model for sinusoidal grating 8 μm pitch, 466 nm amplitude (pk-pk).

The dotted line, shown in figure 3 shows the surface profile that is obtained by finding the peak in the fringe envelope. It can be seen that ideal optics should be capable of identifying the correct fringe and consequently should provide a high quality measure of the surface profile shown in figure 1.

The effect of the PSF becomes more noticeable as the surface gradient increases. For example, if the pitch of the sinusoidal profile is decreased to 3.3 μm the foil model with ideal PSF generates the fringe pattern shown in figure 4. Fringe order errors similar to those shown in figure 1 are now apparent at points where the gradient is steep.

THE EFFECT OF AXIAL ABERRATIONS

It is clear that aberrations will affect the PSF and it is quite straightforward to include axial aberration into the foil model of CSI. In general terms, aberration can affect the responses, $G_i(r, k_0)$ and $G_o(r, k_0)$ of both the illumination and observation optics. When common optics are used in a Mirau objective we would expect the responses to be balanced such that

$G_i(r, k_0) = G_o(r, k_0)$ since the optics to perform both functions are largely the same. Important

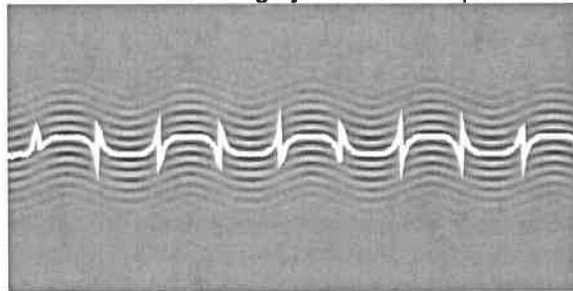


FIGURE 4. Interferogram generated by the foil model for sinusoidal grating 3.3 μm pitch, 466 nm amplitude (pk-pk).

to note, however, that although they are balanced (and appear in both arms of the interferometer), the aberrations will have a residual effect on the PSF and consequently limit the ability to measure steep artefacts. It is also possible to introduce unbalanced aberrations that affect the illumination and observation response in a different way and these can have a greater effect. For example, Mirau objectives of large numerical aperture frequently include a ring that moves the position of the beam splitter within the lens. The effect of this is to change the path length and relative focus between the reference and imaging arms of the interferometer. In general unbalanced aberration has a greater effect on the PSF than balanced aberration and the focus ring is a control that should be adjusted with great caution.

In the following we illustrate the effects of unbalanced and balanced aberration.

Unbalanced Aberration: Defocus

Adjusting the position of the beamsplitter in a high N_A Mirau objective can be modelled by introducing defocus d , into either the illumination or the observation response. From the Fourier shift theorem this is equivalent to a linear phase ramp in k -space and the observation response can be written,

$$G_o(r, k_0) = \int_{-\infty}^{+\infty} e^{j d k \cdot \hat{o}} \frac{\delta(|k| - k_0)}{k_0^2} \text{step}\left(k \cdot \hat{o} - k_0 \sqrt{1 - N_A^2}\right) e^{j k \cdot r} d^3 k \quad (9)$$

The PSF defined by equation (5) can be calculated in this case using the observation and illumination responses defined by equation (9)

and equation (4), respectively. For the typical CSI instrument defined previously the PSF corresponding to a defocus of approximately $2.7 \mu\text{m}$ is shown in figure 5.

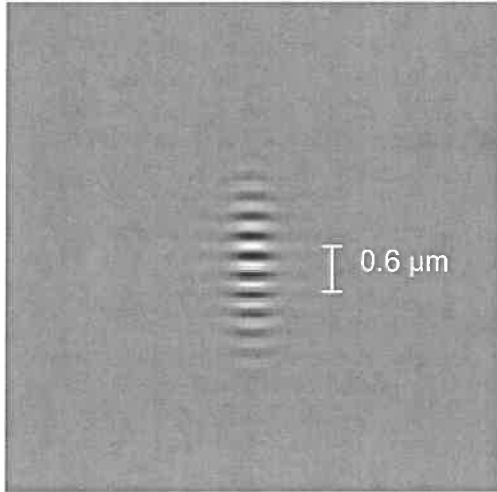


FIGURE 5. PSF with a defocus of $2.7 \mu\text{m}$

With reference to the ideal PSF shown in figure 2, it is noted that the PSF with defocus is larger in both lateral and axial extent. The effect of the defocus on the measurement of a sinusoidal profile with $4.2 \mu\text{m}$ pitch is shown in figure 6.

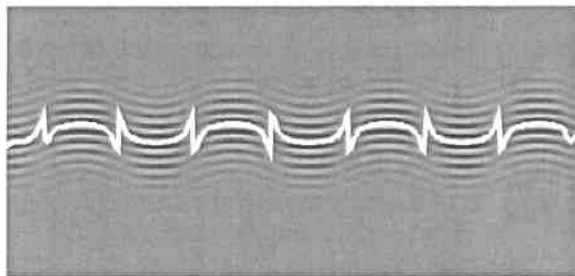


FIGURE 6. Interferogram generated by the foil model for sinusoidal grating $4.2 \mu\text{m}$ pitch, 466 nm amplitude (pk-pk).

Fringe order errors similar to those in figure 4 are now apparent although it is noted that the pitch and hence the maximum gradient of this grating is less.

Balanced Aberration: Axial Chromatic Aberration

Axial chromatic aberration can be thought of as a defocus that depends on wavelength and consequently can be modelled in a similar manner to the unbalanced defocus that was

discussed previously. Writing $d = \alpha / k_0$ where, α is a dimensionless constant and noting that the aberration is balanced we can write,

$$G_o(r, k_0) = G_i(r, k_0) \\ = \int_{-\infty}^{+\infty} e^{j \frac{\alpha k \cdot \hat{o}}{k_0}} \frac{\delta(|k| - k_0)}{k_0^2} \text{step} \left(k \cdot \hat{o} - k_0 \sqrt{1 - N_A^2} \right) e^{j k \cdot r} d^3 k \quad (10)$$

For the typical CSI instrument defined previously, evaluation of the impulse response with axial chromatic aberration is shown in figure 7. In this case the value of α is 2π , which corresponds to a relative defocus of approximately $0.54 \mu\text{m}$ between the wavelengths at the extreme of the spectrum ($1/e^2$ point).

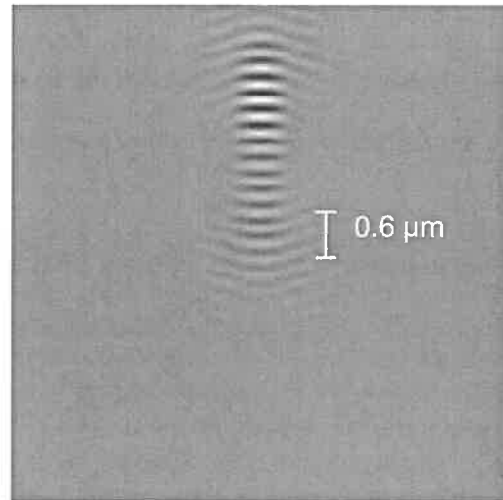


FIGURE 7. PSF with axial chromatic aberration.

The effect of axial chromatic aberration on the measurement of a sinusoidal profile is shown in figure 8. In this case the errors are apparent with a grating of $8 \mu\text{m}$ pitch and are quite smoothly varying.

DISCUSSION AND CONCLUSIONS

In this paper we have considered a linear theory of CSI instrumentation in which the system response can be characterized by its 3D point spread function (PSF) and have argued that this is appropriate to surface profilometry providing that multiple scattering effects are negligible. In this case the scattering from the object surface is equivalent to that from a foil-like object with the same surface profile. We call the application

of the linear theory to an analogous foil-like surface, "the foil model of CSI".

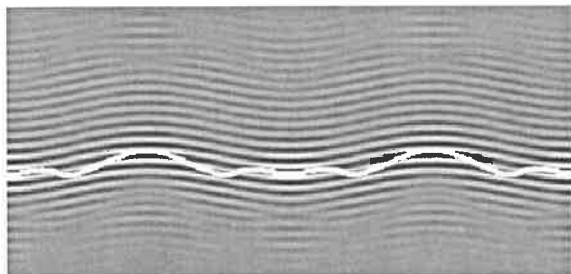


FIGURE 8. Interferogram generated by the foil model for sinusoidal grating 8 μm pitch, 466 nm amplitude (pk-pk).

The foil model of CSI shows that the 3D PSF plays a pivotal role in the characterization of surface form. The PSF can be thought of as a filter that mixes the response from parts of the object within its bounds. If the surface gradient is small, the mixing has little effect and CSI would be expected to work even in the presence of severe aberration. As the surface gradient becomes steeper, however, this mixing has a greater effect on the measurements. In general, the lateral extent of the PSF places a limit on the maximum surface gradient that can be measured. For the ideal case this angle can be visualised as that where the foil model cuts through one cycle in the PSF and this cut-off corresponds to an angle $\theta = \sin^{-1}(N_A)$. At angles less than the cut-off, measurement errors can also occur. Generally, these depend on both the lateral and the axial extents of the PSF and have been illustrated for the case of a sinusoidal profile. We have shown that if the surface profile is deduced purely from the position of the peak visibility in the interference envelope, then the resulting errors will result in fringe order errors that are similar to those reported in practice.

We have also shown that it is straightforward to account for the effect of axial aberrations in the foil model of CSI. Aberrations can be balanced in the sense that they affect both the illumination and observation responses, or unbalanced as in the case of reference field focus that is often offered for adjustment by the user on high power objectives. Unbalanced aberration generally has the most severe effect on measurements but both types of aberration will degrade the ability of CSI to measure steep surfaces. By means of comparison their effect has also been illustrated

for surfaces with a sinusoidal profile and it was shown that the instrument performance degrades significantly with quite modest amounts of aberration.

In this paper the foil model has been used to illustrate the effects of the PSF on CSI measurements. In essence the PSF is a convolution filter that operates on a foil representation of the surface. If the PSF of real instrumentation is known, it follows that interferograms could be improved significantly by a deconvolution process and this is the subject of further work.

ACKNOWLEDGMENT

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INFORMATION EFFICIENT WHITE-LIGHT INTERFEROMETRY

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INTRODUCTION

White light interferometry (WLI) is a precise and versatile tool to measure rough surfaces. However, it requires a big amount of raw data. Increasing demands on measurement speed and camera resolution urge us to reduce the necessary number of camera frames. In comparison to the acquisition of 2D images, where megapixels of data can be acquired "ready to use", 3D images are calculated from big amount of 2D raw images. The number of necessary raw images is at least three for photometric stereo or fringe projection, but it might be several hundreds for white-light interferometry. It is obvious that industry would prefer a sensor that does not need to acquire hundreds of raw images for one single 3D map.

BASIC PRINCIPLE OF WLI

The white-light interferometer ("Coherence radar" [1]) measures surfaces by scanning the temporal coherence function of the broadband light source. For each object point we record a correlogram. From the maximum of the correlogram the position of the corresponding object point along the z-axis can be found.

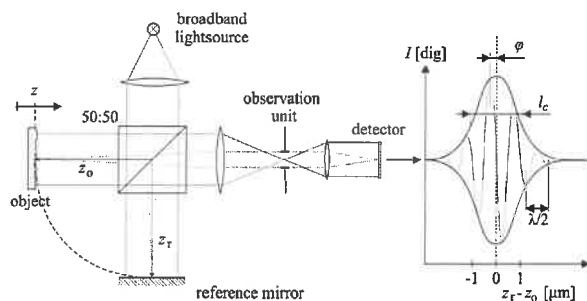


FIGURE 1. Basic principle of white-light interferometry; left: measurement setup, right: correlogram with the maximum of the envelope at $z_o - z_r = 0$.

INFORMATION-THEORETICAL MODEL

If we consider WLI as a communication channel [2], the question of how to increase the speed is the question how to acquire maximum information with a minimum amount of 2D raw

data. Information from a source (surface under test) is encoded (by illumination) and sent through a channel (optics, electronics, mechanics) into the decoder (evaluation algorithm).

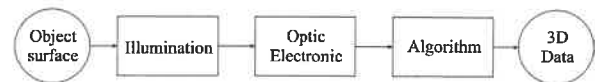


FIGURE 1. Transmission model of optical 3D sensors

The performance of a sensor is mainly limited and the cost is given by the channel capacity. We need less channel capacity by redundancy reduction through proper source- and channel encoding.

A typical power spectrum of a surface shape displays much low frequency energy, and strong zero component (stand-off) (FIGURE 2.).

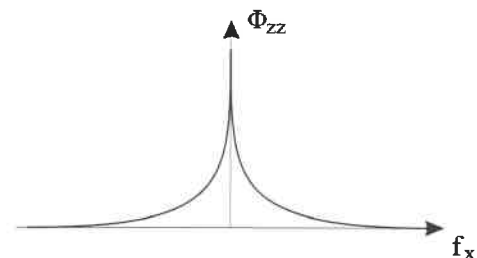


FIGURE 2. Typical power spectrum of surface shape $z(x,y)$.

An optimal source encoding strategy is whitening the power spectrum and suppressing the stand-off information by slope-measuring (differentiating) sensors. It is interesting that classical interferometry suppresses the stand-off information as well. However, this is not the case for WLI. We will discuss options how to make WLI more information efficient.

The information efficiency is defined as the ratio of realized mutual information in the 3D height map and the available channel capacity. The mutual information is dependent on the scanning range Δz and on the achievable measurement uncertainty δz . The channel capacity per pixel is

given by the signal-to-noise ratio S_{2D}/N_{2D} and the number M of acquired camera frames:

$$\eta = \frac{\text{mutual information}}{\text{channel capacity}} = \frac{\log_2\left(\frac{\Delta z}{\delta z}\right)}{M \cdot \log_2\left(\frac{S_{2D}}{N_{2D}}\right)}.$$

To simplify further comparison of measurement results, we simplify the information efficiency as

$$\eta = \frac{1}{M} \cdot 100[\%].$$

INFORMATION EFFICIENT WLI

Source Encoding

The first option for efficient WLI is to adapt the reference in a way that only small **height differences** to the object under test occur. The Twyman Green interferometer is the classical example to measure spherical surfaces. Another solution to increase the information efficiency is to adapt the object illumination, if the a-priori information about the basic shape of the measured surface is known. Adaptation means to adjust the direction of the incoming rays perpendicular to the surface. One example is the measurement of conical [3] and inner-conical surfaces (FIGURE 3, 4).

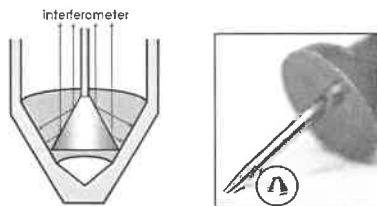


FIGURE 3. Left: Measurement of an inner-conical surface, right: Used 60° conical micro-mirror (Ø1.6mm).

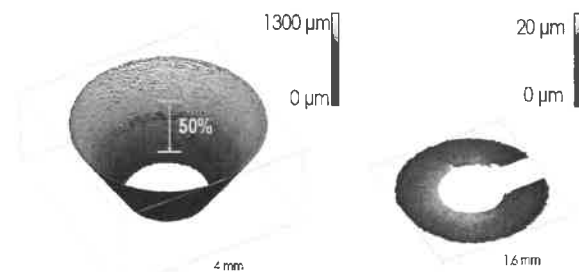


FIGURE 4. Left: Standard measurement (4000 frames), right: Adapted illumination via conical mirror (120 frames).

With the coherence radar (WLI on rough surfaces) we can measure nearly any rough object against its rough master reference. The ultimate solution to reduce the number of acquired raw data is to put a master object with a comparable surface profile in the reference arm. This offers very efficient quantitative comparison, because we are detecting only relative differences between the master and the measured object.

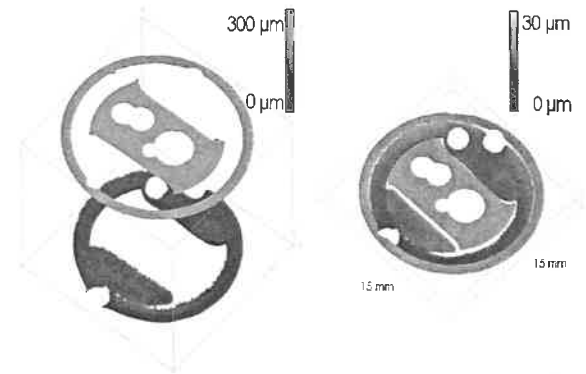


FIGURE 5. Part of injection system for engines. Left: Standard measurement (1900 camera frames), right: Adapted reference arm (190 camera frames).

The same principle can be adapted to measure very large objects (>100mm) by WLI (FIGURE 6.) The mirror in the reference arm is replaced by an optically rough reference plane. The large measurement field is achieved by divergent illumination and observation.

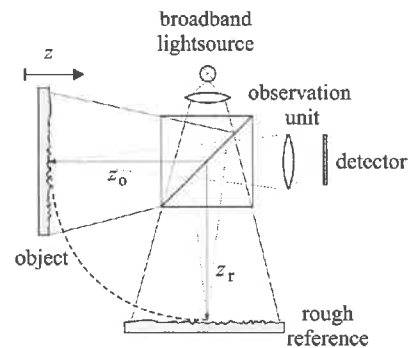


FIGURE 6. Basic principle of WLI with rough reference plane.

The maximum achievable measurement uncertainty is limited by the roughness of the reference surface.

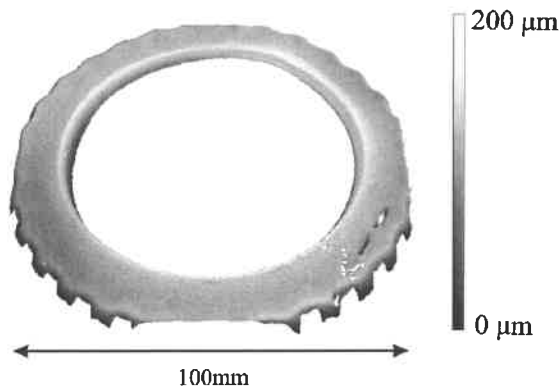


FIGURE 7. Measurement of the clutch ring with 100mm in diameter.

Channel Encoding

In a communication system, the channel encoder re-inserts redundancy to the source signal in order to minimize the error probability caused by the noisy channel, and to enable fast and effective decoding by a proper evaluation algorithm. WLI standard evaluation algorithms are based on **reconstruction** of the correlogram carrier. To find the maximum requires the full reconstruction of the modulation of the correlogram. The envelope is then reconstructed from the modulation. This leads to the physical limit given by Shannon's Sampling Theorem [4,5].

For a measurement range of $\Delta z = 100\mu\text{m}$ and for a wavelength of $\lambda = 800\text{nm}$ the efficiency is only $\eta_{\text{standard}} = 0.2\%$.

Deep objects require a big amount of raw image acquisition, which commonly is reduced by careful undersampling. The Sampling Theorem for bandlimited signals offers high reduction of the acquired images, but at the cost of a more accurate sampling. The practical limit is 10x undersampling with an efficiency of approximately $\eta_{\text{undersampling}} = 2\%$.

We present a measurement strategy based on direct reconstruction of the envelope of the correlogram [6]. Principally, only 6 raw images are necessary to acquire the correct shape of surface. The modulation is not reconstructed, because the contained information is useless for rough surfaces. With use of the Hilbert transformation H the real signal (correlogram) $c(z)$ is transformed into the complex signal $C(z)$

$$C(z) = c(z) + iH\{c(z)\} = E(z)e^{i\varphi(z)},$$

where $E(z)$ is the envelope of the correlogram. From the geometrical properties the envelope can be extracted:

The Hilbert transformation works as a 90° phase-shift-function:

$$E(z) \approx \sqrt{[c(z)]^2 + [c(z + \lambda/8)]^2}.$$

We propose a measurement strategy, where both quadratures $\text{Re}\{C(z)\}$ and $\text{Im}\{C(z)\}$ are measured. One point of $E(z)$ is acquired from two 90° shifted exposures (FIGURE 8.).

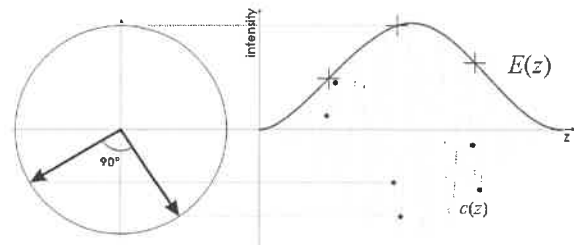


FIGURE 8. Demodulation scheme of direct envelope reconstruction.

Three-point-Gauss-interpolation is the standard solution to find the maximum. We need only 3 envelope points and therefore only 6 camera frames. The localization of the envelope maximum is limited by the envelope width and by the number of acquired sampling points.

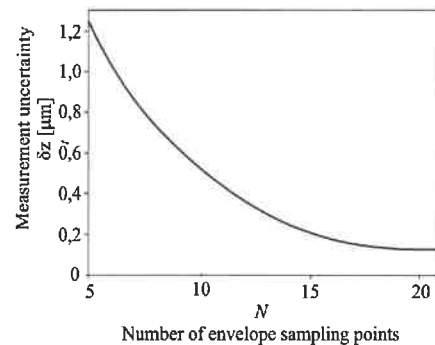


FIGURE 9. measurement uncertainty vs. the number of envelope sampling points $N = M/2$ (from experiment)

For practical reasons, we are sampling 5 envelope points and the resulting information efficiency is $\eta_{\text{quadrature}} = 10\%$! (FIGURE 10.)

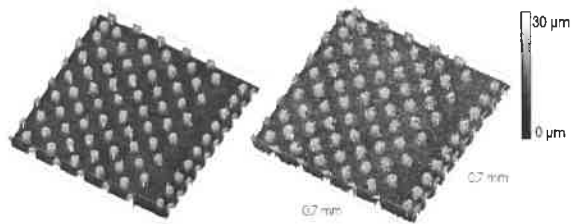


FIGURE 9. Measurement of ball-grid array. Left: Properly sampled (500 frames), right: Direct envelope reconstruction (10 frames).

Summary

The table displays the comparison of the presented evaluation methods for a measurement range of $100\mu\text{m}$ and $\lambda = 800\text{ nm}$. It is assumed, that the measured surface is optically rough.

TABLE 1. Information efficiency/comparison.

	Information efficiency	measurement uncertainty
Evaluation according to sampling theorem		
Undersampling	$\eta_{\text{under-sampling}} = 2\%$	
Quadrature demodulation:		$\delta z = 1\mu\text{m}$

Quadrature demodulation displays 50x higher information efficiency without necessity of extremely precise sampling, which is required by undersampling methods.

It should be noted that Table 1 does not consider the achieved dynamical range of the output data. This means, the information efficiency the standard evaluation is slightly better than given in Table 1.

We cannot quantitatively define the efficiency of the measurement with adapted illumination or measurement setup with rough reference, because the result is always dependent on the shape of the measured object. Table 2 summarizes only the efficiency for the presented examples (FIGURE 4 for adapted illumination and FIGURE 5 for adapted reference arm).

TABLE 2. Information efficiency for adapted illumination and reference.

Adapted illumination		
Adapted reference arm		

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QUANTIFICATION OF MICRO-SCALE SURFACE CHANGES USING INTERFERENCE MICROSCOPY

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White-light interferometry, or optical profilometry, has provided quantifiable three-dimensional surface metrology on surfaces for over 25 years. This technique, which employs an optical microscope modified with a specialized objective and precision scanner, is capable of measuring a wide variety of surfaces, including foam, paper, machined metal, polished glass, and plastics with sub-nm vertical resolution. By changing microscope objectives, fields of view from 15mm to 20 μ m may be imaged in a single field of view

Recent improvements in vertical resolution and analysis capabilities are finding new applications for white-light interferometry in areas such as tribology and corrosion. The system's high vertical resolution, non-contact nature, and rapid measurement time allow quantification of minute changes in surface morphologies. State-of-the-art optical profilers such as Veeco's NT9800 can detect very shallow scratches such as the approximately 0.2nm depth polishing marks on a SiC surface. Each measurement takes only a few seconds, so many measurements may be made during wear or polishing studies to see the effect of different processes on surface finish

Such quantification of surface changes is especially important for studies of corrosion. Stainless steel corrosion coupons are measured before and after corrosion has begun to attack them. Fiducials are automatically found via software so that parts are lined up identically between measurements. This allows in-depth studies of the effect of roughness, local defects, surface slope and other variables on the onset and spread of corrosion across surfaces. Pits are automatically identified and the software can calculate the number, depth, area, and volume of features that exceed a given threshold. Multiple measurements may be combined to form a video for rapid visualization of the corrosion process. It is found that some features deepen with the onset of wear, though some other steep surface features do not seem to seed corrosion sites. Corrosion experiments

are critical in the study of petroleum and chemical transport systems, medical implants, drug preparation equipment, batteries, and solar installations as contamination and lifetime requirements tighten.

Similarly, increased lifetime and performance requirements on load-bearing and cutting surfaces enhance the need to rapidly and accurately quantify wear. Surfaces are measured throughout their lifetime or during specialized experiments to quantify the amount and severity of wear, as well as the effect of lubricant or other variables on the wear process. Veeco has studied various cutting surfaces from a new state to a highly worn state. The surface roughens significantly and becomes far more random as it is used. With their ability to quantify height as well as lateral features without sample preparation and in a non-contact manner, white light interferometric microscopes are ideal for tracking surface changes over time. Tribological applications include analysis of clutch plates, breaks, air bearing stages, surgical implements, engine and turbine parts, and orthopedic implants.

SCALE-BASED COMPARISON OF INTERFEROMETRIC, CONFOCAL AND STYLUS MEASUREMENTS AND THEIR ABILITY TO DISCRIMINATE

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INTRODUCTION

The objective of this work is to quantify the differences in measurements from selected confocal, interferometric and mechanical stylus instruments in terms of the scales as well as the ability to discriminate parts ground with different grits.

This is important because knowledge of the differences between instruments and of the ability to discriminate parts ground with different conditions could facilitate instrument selection for certain tasks. Understanding the differences could aid in the comparison of measurements from different instruments and the design of algorithms to filter and interpret the measurements.

Differences between texture measurements made by interferometric microscopes and other texture measurements have been noted previously. Rhee et al. found that measurements of periodic gratings and a "random specimen" showed greater Ra values for white-light interferometry (WLI) than for phase-shifting interferometry (PSI). The profiles they published showed that there are more irregularities on WLI measurements than on PSI. The WLI measurements also showed greater standard deviations on step height measurements than did PSI[1]. Gao et al. discuss the batwing effect observed around a step discontinuity and attribute it to "interference between the reflections of waves normally incident on the top and bottom surfaces following diffraction from the edge". They conclude that "the most frequently occurring errors are jumps or spikes of half the mean wavelength" which tend to occur on steep slopes

or steps[2]. Earlier, Harasaki and Wyant used a diffraction model to simulate batwings[3].

Conventional characterization parameters as well as relative lengths and relative areas as a function of scale are used to characterize the profiles and textures [4]. Previously F-tests have been used to test for the ability to discriminate [5-6] in this work the Mann-Whitney U-test is used to test for the ability to discriminate, both between surfaces ground with different grit sizes and between instruments measuring the same surface. The Mann-Whitney U-test, a non-parametric median test, is used at each scale to determine if the median relative lengths can discriminate at each scale.

The Mann-Whitney U-test calculates the probability (p-value) that two groups of measurements have the same median. A low p-value indicates that the medians can be discriminated. This test was selected because the test does not make any assumptions about normality [7].

METHODS

Silicon carbide cup wheels (with a diameter of 30 mm and a wall thickness of 3 mm) with three different grit sizes (600, 800 and 1000) corresponding to nominal grain diameters of 9, 7, and 5 μm were used to grind four flat surfaces on the ends of 13 mm diameter cylinders with a 3 mm hole in the center made from SAE 51200 steel at 60 HRC. Oil based coolant was used during the grinding. The cups wheel was rotated at a speed of 6000 rpm in the opposite direction of the part's rotation of 1000 rpm. The cup wheel was feed at a rate of 15 $\mu\text{m/s}$. The outside diameter of the cup wheel passed through the center of the part at a depth of 100 μm . A

Supfina SM813-W2 grinder was used in a process similar to that use in industrial for finish grinding flat surfaces with a cross hatch.. A total of 4 surfaces were prepared with each of the grit sizes. The surfaces were measured on an Olympus LEXT OLS4000 laser scanning confocal microscope (LSCM), a Vecoo WYCO NT8000 (WLI), and Taylor Hobson Form Talysurf Series 2 PGI (stylus).

The Olympus LEXT OLS4000 is a vertical scanning laser confocal microscope with a 408 nm violet laser light. The stated planar resolution is 120 nm for the 100X objective, with a height resolution of 10 nm. The 100X objective, with a numerical aperture of 0.95, was used for these measurements. The sampling interval at this magnification is 125 nm, with a measurement region of 128 x 128 μm^2 . Twenty-five texture measurements were stitched together with approximately 10% overlap for a stitched measurement region of 1.17 x 1.16 mm. A total of four texture measurements with 4700 x 4600 elevations, with a sampling interval of 0.25 μm were made on each of the three grinding conditions.

The WLI Veeco WYKO NT8000 interferometric microscope was operating in the white light mode. It was configured with a nominal 50x objective lens (NA~ 0.5) with a nominal 0.55X field of view lens, providing an effective magnification of 26.3X. The vertical height resolution of the WYKO NT8000 is typically less than 6nm. The lateral sampling established by the optics and camera resolution was ~ 0.75 μm . Note however that the diffraction limited optical resolution is typically ~ 1 μm . A single image measurement provides a measured area of 240 x 180 μm . Fifty-four measurements were stitched together to provide the 1.2 x 1.2mm field of view for this study. Twelve texture measurements with 1596 x 1596 elevations were made with a sampling interval of 0.75 μm on each of the three grinding conditions.

The Taylor Hobson Form Talysurf Series 2 PGI used a 2 μm radius stylus with a tracing speed of 0.5 mm/s over a tracing length of 1.5 mm and the evaluation length was 1.25 mm. The sampling interval was 0.25 μm for a total of 5000 elevations in the evaluation length.

RESULTS AND DISCUSSION

Figure 1 shows that, at scales finer than about 10 μm^2 , the mean relative areas calculated from

measurements made by the WLI are greater than those from the LSCM. Figure 2 shows that the rank of the instruments by mean relative lengths from greatest to smallest is: WLI, LSCM, and stylus. All instruments rank the surfaces ground with 600 as having the greatest relative lengths and the surfaces ground with 1000 grits having the smallest relative lengths at the smallest scale.

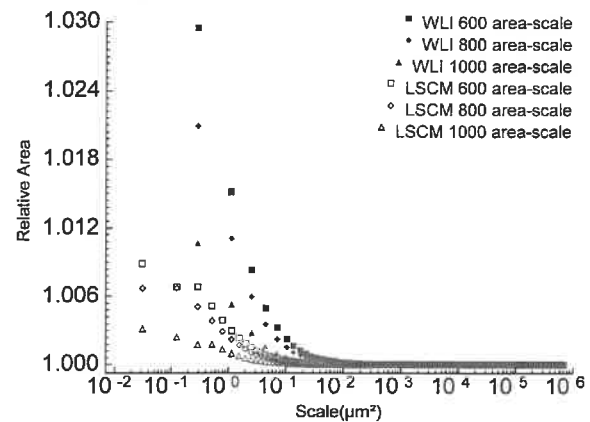


Figure 1. Mean relative area vs. scale for WLI and LSCM measurements of surfaces (all grit sizes)

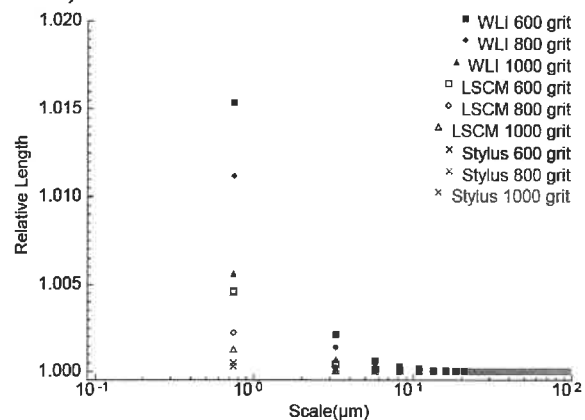


Figure 2. Mean relative length vs. scale for WLI and LSCM measurements of surfaces (all grit sizes)

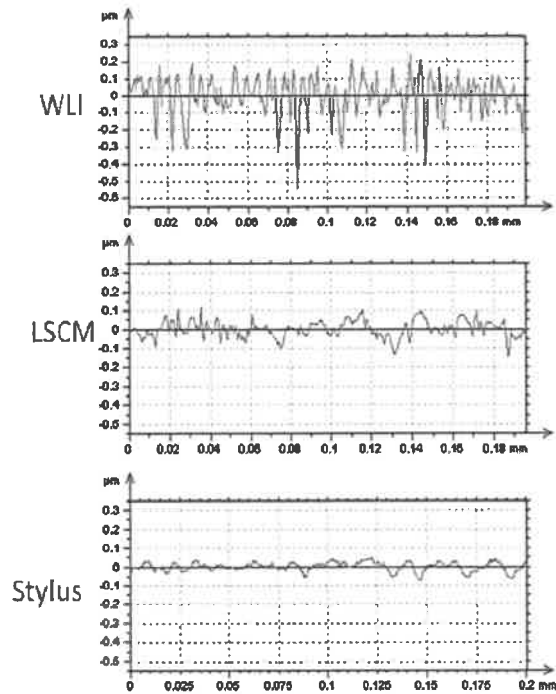


Figure 3. Extracted profiles from 800 grit surfaces measured by each instrument

Figure 3 shows typical profiles from the three instruments from a surface ground with 800 grit. The profiles were extracted from areal measurements on the WLI and the LSCM. The profile from the WLI appears to be the most intricate followed by the LSCM and the stylus. This is consistent with the rank by relative area and relative length (Figures 1 and 2). However the height parameters tend to be greater for the stylus than for the LSCM in most cases (Table 1). In this case at least the relative length correlates better with an aesthetic sense of intricacy of the profile than do the height parameters. Features in the profile from the WLI appear similar to the bat wings noted by other researchers [1-3].

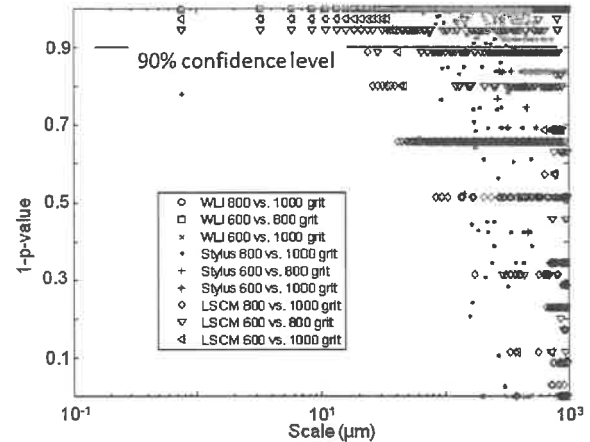


Figure 4. One minus p -value vs. scale for relative length comparing all grit sizes using measurements from all instruments

There are differences between the ability of the instruments to discriminate the surfaces. Figure 4 shows the instruments and their ability to discriminate surfaces ground with different grit sizes. With one exception, the surfaces ground with different grits can be discriminated by the relative lengths calculated by measurements from all instruments at scales less than 20 μm . The one exception is that the relative lengths calculated from the stylus measurements cannot discriminate the surfaces ground with 800 versus 1000 grit at the finest scale, i.e., 0.1 μm . However the stylus can discriminate these surfaces at scales below about 100 μm , which are larger than the scale, 20 μm , below which the LSCM begins to discriminate. It should be noted that there are fewer measurements from the LSCM than from the WLI and stylus. It is likely that the ability to discriminate would change, if more measurements were used in the analyses. More work would be required to generalize on the instruments' abilities to discriminate.

Figure 5 shows that at scales finer than about 10 μm all instruments can be discriminated from each other using relative lengths calculated from measurements of similar surfaces prepared with any of the three grit sizes. Potentially interesting information derived from the scales of discrimination the instruments, and from the instruments' scale of discrimination of the surfaces, could be present in these analyses, although it would require more work to extract it.

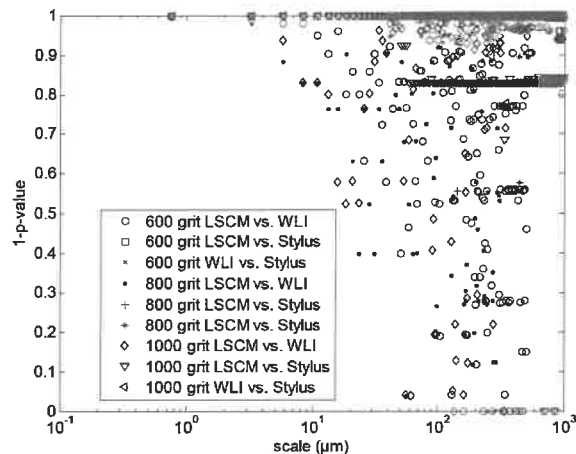


Figure 5. One minus p -value vs. scale for relative length comparing instruments for all grit sizes

The medians, means and standard deviations of R_z , R_a , R_q and R_{sk} values, calculated according to ISO 4287 [8] (Gaussian filter $\lambda_s = 2.5 \mu\text{m}$, $\lambda_c = 0.25 \text{ mm}$) for the three instruments

are summarized in Table 1. The median values of R_z , R_a , and R_q calculated from profiles measured by the LSCM and stylus instruments are closer to each other than they are to the WLI median values. R_z , R_a , and R_q values calculated from WLI measurements are significantly higher than those from either the LSCM or stylus measurements. Significance was determined with the criteria of a $p\text{-value} < 0.1$ as calculated by the Mann-Whitney U-test. R_a is roughly double when calculated from measurements made on the WLI vs. the stylus instrument. This is consistent with Rhee et al. who stated that R_a was 107% larger on the WLI than the stylus instrument [1]. The trend for the R_{sk} values is not clear; however all instruments measure a negative skew. All instruments can be discriminated from each other using all parameters except R_{sk} calculated from measurements of all parts ground with all three grit sizes.

		$\lambda_s = 2.5 \mu\text{m}$, $\lambda_c = 0.25 \text{ mm}$ Gaussian filter											
	Grit size	$R_z \text{ (nm)}$			$R_a \text{ (nm)}$			$R_q \text{ (nm)}$			R_{sk}		
		median	mean	St. Dev.	median	mean	St. Dev.	median	mean	St. Dev.	median	mean	St. Dev.
LSCM	600	360.1	359.6	48.0	44.7	44.7	4.8	57.6	57.5	6.4	-0.63	-0.61	0.11
	800	221.2	253.1	68.0	29.8	32.4	6.8	38.2	42.0	9.5	-0.67	-0.77	0.25
	1000	162.8	166.3	21.5	22.0	22.3	2.5	28.1	28.4	3.2	-0.43	-0.45	0.10
WLI	600	520.3	531.0	26.2	78.5	78.3	4.9	98.6	98.4	5.5	-0.42	-0.42	0.08
	800	423.5	441.9	73.5	60.6	61.7	10.4	77.2	78.8	12.7	-0.71	-0.68	0.10
	1000	330.8	322.1	31.9	48.2	49.9	7.0	54.4	54.7	5.6	-0.74	-0.70	0.22
Stylus	600	354.2	336.3	39.1	47.4	47.1	4.3	60.8	59.7	5.6	-0.17	-0.05	0.45
	800	261.9	245.9	54.2	32.2	32.2	5.3	42.8	41.5	7.2	-0.33	-0.33	0.41
	1000	180.4	181.7	13.6	23.9	23.9	1.7	30.5	30.7	2.2	-0.53	-0.52	0.16

Table 1. Summary of values of R_z , R_a , R_q , and R_{sk} . Text with white background indicates that all parts ground with all grit sizes can be discriminated. Text with gray background indicates that at least one combination of parts cannot be discriminated using the Mann-Whitney U-test.

CONCLUSIONS

1. There are significant differences between texture characterization parameters calculated from multiple measurements from ground surfaces.

2. Despite significant differences in the characterization parameters derived from the different instruments, all the instruments can make measurements that are capable of discriminating the three surfaces ground with different grit sizes that were used in this study.

3. The measurements made with the WLI are more intricate and rougher as quantified by height parameters and by relative lengths below scales of 10 μ m at least and by relative areas at scales below about 30 μ m².

ACKNOWLEDGEMENTS

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A STUDY ON RESPONSE PROPERTIES OF SURFACE TEXTURE MEASURING INSTRUMENTS IN TERMS OF SURFACE WAVELENGTH

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1. INTRODUCTION

It is important to control the surface quality and texture of manufactured parts for advanced industrial products. While many types of surface texture measuring instruments appear on the market, optical instruments are increasingly being adopted because they perform non-contact measurements and can easily measure a surface area instead of a simple line profile. Measurements by optical instruments are based on different principles and do not always correlate to each other [1][2][3]. The uncertainty in correlation raises some concerns by the users regarding the reliability of the measurement. This study aims to explain the reliability of surface measurements performed by optical instruments. To begin with, we took measurements of test samples using a different instruments based on differing technologies. Next, we examined what caused differences between the measurements. Lastly we studied how we could improve the correlation of the measuring results among these measuring instruments.

2. INSTRUMENTS AND SAMPLES

The following optical instruments were studied: a Laser Scanning Microscope (LSM), a Coherence Scanning Interferometer (CSI), and a

Point Auto-Focus probe (AF). For LSM and CSI, we changed the measurement condition by using objective lenses of different magnification. We also used a stylus instrument as a reference. The measuring conditions of the respective instruments are shown in *TABLE 1*.

Samples are one-dimensional grating standards which have a cross-sectional shape of sinusoidal or rectangular patterns of 0.24 – 100 micron period and 0.1 – 1.5 micron peak-valley value. *TABLE 2* displays the sample list.

We define amplitude response properties, as the ratio of a measurement result to the nominal peak-valley value in the vertical direction. The results are examined in terms of the cycle of the grating structures called as "surface wavelength".

3. RESULTS

FIGURE 1 and *FIGURE 2* show cross sectional profiles acquired by each instrument. The profiles are arranged in a way that a profile of higher position is acquired by a higher N.A. objective lens. The profile of the stylus instrument is shown at the bottom of each graph. As shown in *FIGURE 1*, measured profiles of Rubert No.528, which has a surface wavelength of 50 μ m, every profile shows almost the same amplitude.

On the other hand, as shown in *FIGURE 2*, measured profiles of Rubert No. 543, which has a surface wavelength of 2.5 μ m, although the profiles (a) and (b) show the approximately the same amplitude as the nominal value, the other profiles show different amplitudes. In particular, it should be noted that the lower N.A. has, the larger the amplitude as shown in the profiles (c) ~ (e). From this result, we have found that the amplitude response property is affected by the N.A.

The profile (g) by the stylus instrument shows smaller amplitude than the nominal value. This

TABLE 1. Measuring instruments and conditions

Instrument	condition
LSM: Laser Scanning Microscope	20xNA0.6
	50xNA0.95
	100xNA0.95
CSI: Coherence Scanning Interferometer	20xNA0.4
	50xNA0.55
AF: Point Autofocus probe	100xNA0.8
Stylus	Tip radius 2 μ m

TABLE 2. Geometrical specifications of the samples

Sample	Nominal Surface Wavelength (μm)	Nominal Amplitude (μm)	Shape
Rubert [4] No.531	100	1	Sinusoidal
Rubert No.528	50	1.5	
Rubert No.529	10	0.3	
Rubert No.542	8	0.2	
Rubert No.543	2.5	0.12	
NTT-AT NIM-PH350	20, 6, 4, 2, 1.6, 1.2, 1.0, 0.8, 0.7	0.35	Rectangular
Elionix Line & Space (resist pattern)	0.4, 0.36, 0.32, 0.28, 0.24	0.1	

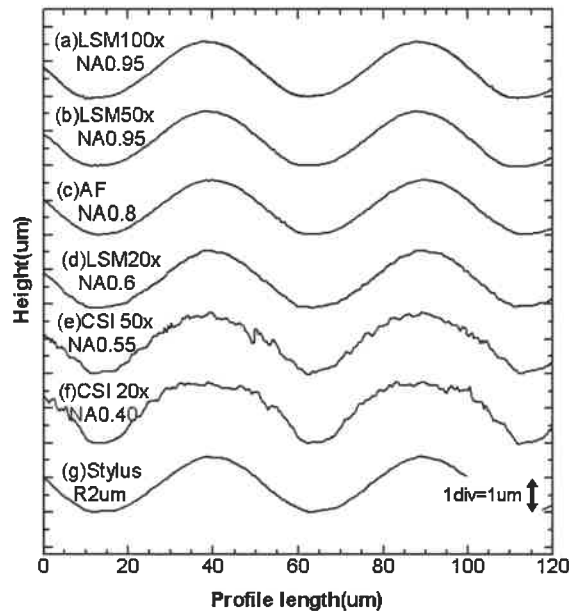


FIGURE 1. Measured profiles. Rubert No.528 (Wavelength: 50 μm , Amplitude: 1.5 μm)

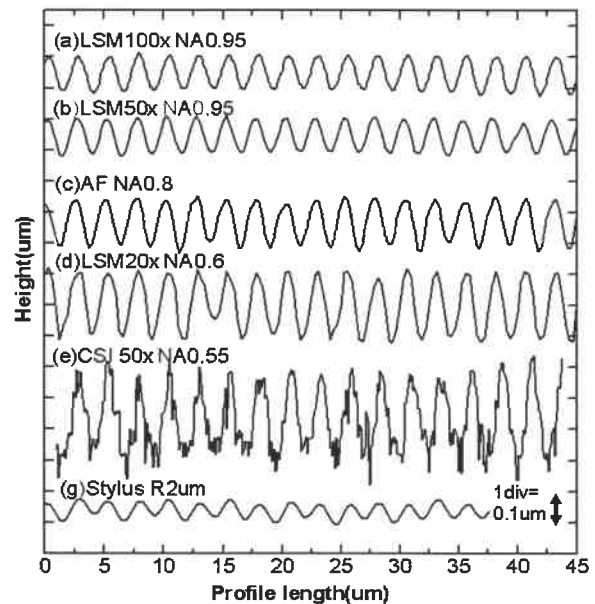


FIGURE 2. Measured profiles. Rubert No.543 (Wavelength: 2.5 μm , Amplitude: 0.12 μm)

is because λ s profile filter ($\approx 2.5\mu\text{m}$) [5] is embedded in the instrument.

FIGURE 3 shows the profiles of even shorter surface wavelength sample. At this point, only the LSM using the objective lens of 100x, N.A.0.95 is used for comparison, since the LSM of this criteria shows a solid response property in FIGURE 2. Five samples are measured, and these surface wavelengths are under the diameter of the beam spot ($\div \lambda / \text{N.A.} = 0.405\mu\text{m}/0.95 \div 0.4\mu\text{m}$). Sampling interval in the lateral direction is below 1/15 of the minimum surface wavelength, i.e. $dx=0.016\mu\text{m}$,

which is small enough to remove the effect of the sampling interval.

The measured amplitude of the profile (a1) is about 0.15 μm . The shorter the surface wavelength is, the less amplitude of the profile (a2) ~ (a5) for. These five nominal wavelengths are also measured by an AFM, and the measurements are nearly the same as the nominal value, i.e. 0.09~0.1 μm . Therefore, while the profile (a1) ~ (a3) show higher amplitude than expected, the profile (a5) shows lower amplitude.

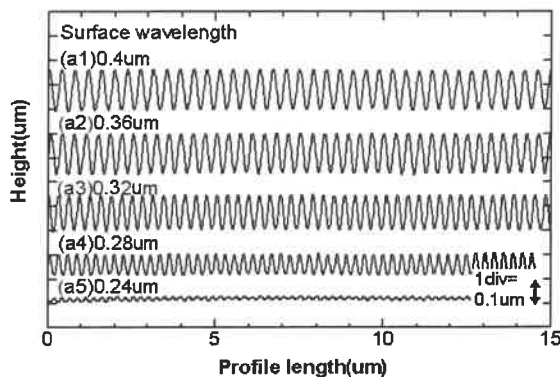


FIGURE 3. Profiles measured by LSM using 100x objective lens. The test sample is Elionix Line&Space (Amplitude: 0.1 μ m)

4. AN INTERPRETATION OF THE RESPONSE PROPERTIES

FIGURE 4 shows the graph of the relationship between amplitude response and surface wavelength.

In the range where the surface wavelengths are between 20 and 100 microns, the response properties of the measurements of the optical instruments and all conditions are almost equal to 1, which means the result is equal to the nominal value.

When it comes to the range of shorter surface wavelengths below 10 μ m, amplitude response may exceed 1.

We consider the phenomenon of larger response properties more than 1 as an overshooting spike that is peculiar to optical instruments.

The overshooting surface wavelength differs depending on the instruments and measurement conditions, so this explains the difference between the measurements by different instruments.

On closer examination of the results of LSM data (a) and (b), we realized that the overshooting surface wavelength of LSM is close to the size of a beam spot. ($\approx \lambda / N.A. = 0.405\mu\text{m} / 0.95 \approx 0.4\mu\text{m}$)

It is said that the overshooting spike is caused by the interference of reflected light from minute unevenness in a small laser beam spot [6]. We consider this phenomenon appeared in the actual results of our measurements.

In the range of surface wavelength where it is shorter than the overshooting wavelength, amplitude response falls sharply from the original position.

This phenomenon does not only appear with the optical instruments, but the stylus instrument shows a similar decrease of amplitude response against the short surface wavelength. This phenomenon is due to the size of the probe; stylus for stylus instrument, and beam spot for optical instruments.

The reason why data (a) and (b) show the similar response properties is because the size of beam spots are approximately the same due to the same N.A.

The responses of CSI (e), (f) are overshooting around the wavelength, 8 micron, which is longer than the diameter of the size of the optical probe, that is calculated from the N.A. and the illumination wavelength ($\approx \lambda / N.A.$)

The result leads to our presumption that the reason for the overshooting spike was not the actual response to the nominal wavelength of the surface, but minute unevenness, in other words an extremely short wavelength.

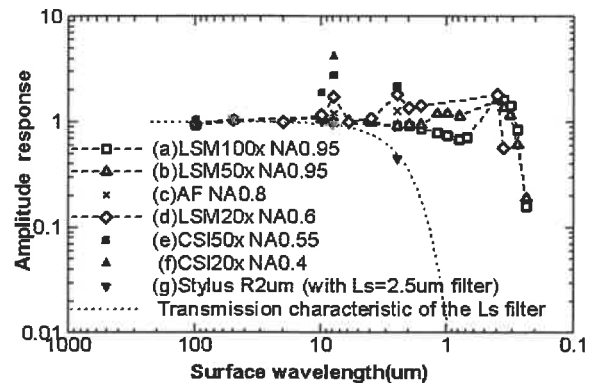


FIGURE 4. Response Properties of surface texture measuring instruments in terms of surface wavelength

5. TO IMPROVE THE RELIABILITY OF MEASUREMENT BY NON CONTACT MEASURING INSTRUMENTS

According to ISO [7] for the stylus instruments, the following two points are necessary to improve the accuracy of the comparisons between instrument to instrument, or between surface to surface.

- (a) Introducing of the λ s-filter (short cut-off filter)
- (b) Providing the means to define the measurable limit of a measuring instrument to the direction to the short wavelength components

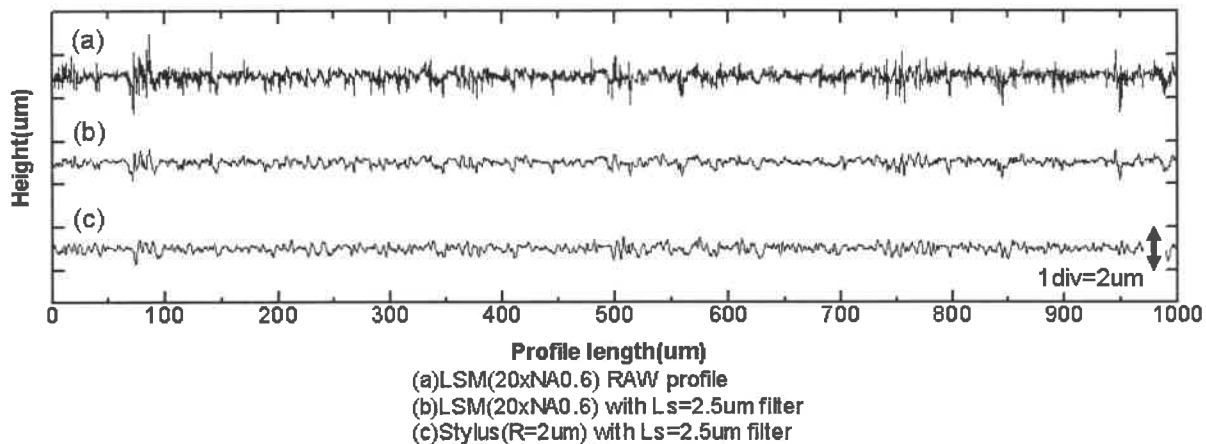


FIGURE 5. The effect of the λ_s -filter (short cut-off filter) in the comparison. The test sample is Rubert random roughness specimen No.504 [4]

In the following section, we applied (a) to the result of LSM and compared it against the result of the stylus instrument and studied practical method for (b).

5-1. The Introduction of the λ_s -filter

FIGURE 5 shows the result of the comparison of the LSM with the λ_s -filter against the stylus instrument. While there are many overshooting spikes in the RAW profile of the LSM (a), those spikes are removed in the λ_s -filtered profile (b), and it correlates with the stylus profile (c).

As the result demonstrates, we can improve the accuracy of the comparison even in the case of different measuring techniques by the comparison between the filtered profiles of (b) against (c).

Stylus instruments have an embedded λ_s -filter to maintain the equivalence among instruments. The λ_s -filter eliminates the components of shorter wavelength, which is limited by a finite size of a stylus. For example, when the stylus tip radius is 2 μm , it is decided in ISO [7] that the short cut-off filter $\lambda_s=2.5\mu\text{m}$ is applied. Similarly, it is appropriate to have a λ_s -filter that corresponds to a respective instrument's critical limitation to ensure the correlation among measuring instruments. Examination of the response properties that we showed in FIGURE 4 is necessary to determine the rational cut-off value of λ_s filter.

5-2. Means of Defining Limits of Instrument Operation

In order to obtain the response properties shown in FIGURE 4, samples with various wavelengths have to be prepared, however it is not practical method for the periodic verification of the measurement instrument.

Accordingly, we made the test chart shown in FIGURE 6, which enables us to obtain the response properties easily. The chart has a portion of the star pattern, which is used for resolution measurements in the field of "Imaging" [8][9]. The chart patterns have continuous pitches from 3.5 μm to 0.2 μm , and have 80nm step height made of silicon; therefore, we can obtain the responses in all of the wavelength range at one time.

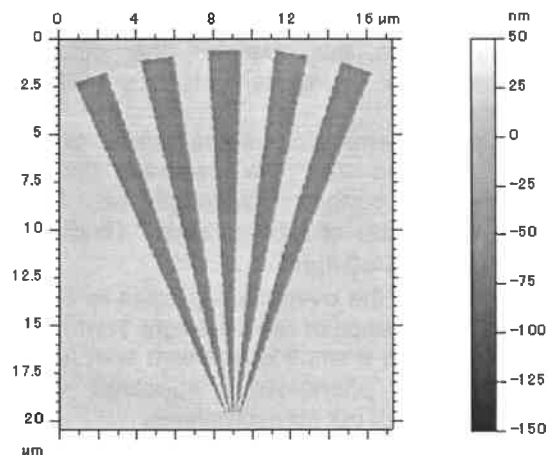


FIGURE 6. The star pattern chart measured by AFM

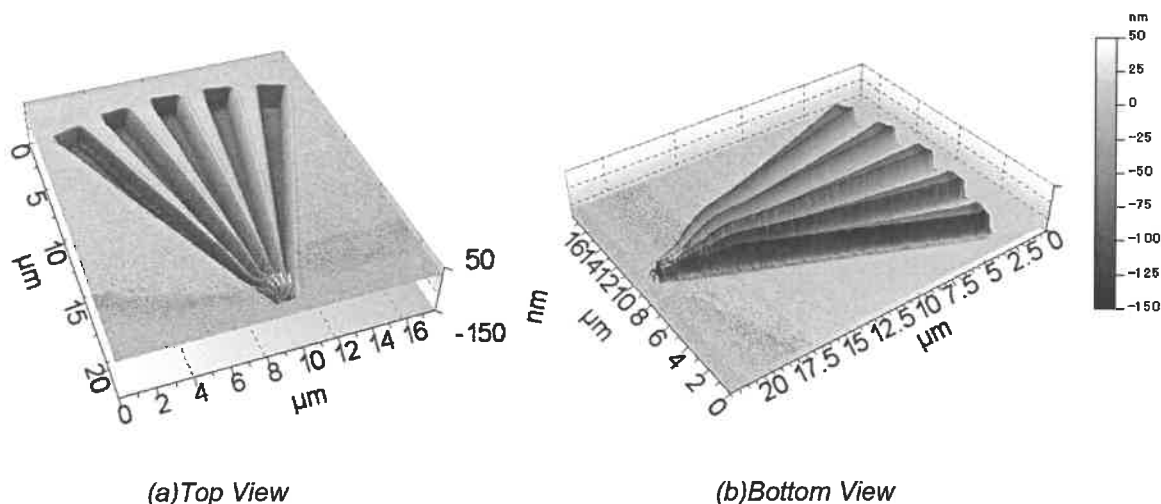


FIGURE 7. Isometric view of our star pattern chart measured by LSM 100x N.A.0.95

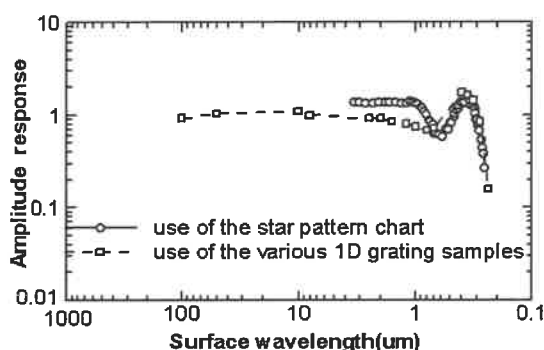


FIGURE 8. The evaluation of response properties by the star pattern chart. (LSM 100x N.A.0.95)

FIGURE 7 shows the measuring result of LSM with 100x NA 0.95 objective. We confirmed that the measured amplitude is continuously varied as the chart pattern pitch narrows.

The response properties we examined from the measuring result are shown in FIGURE 8. For comparison, we plot the response of FIGURE 4 as well. In confirming the close relation, we consider that our star pattern chart is a useful sample to examine the response properties of a measuring instrument.

Additionally, the reason that the response is above 1 in all the longer wavelength section is the effect of the rectangular shape, which has an extremely short wavelength as its component. If the sectioning shape of the sample is sinusoidal, we surmise that the response properties for the section of with longer wavelengths will become 1.

6. CONCLUSION

- 1) As a result of our experiment, it is demonstrated that overshooting surface wavelength differs depending on the instruments and measurement conditions, and this fact creates the differences between instruments. It is also confirmed that phenomena such as overshooting spike in the short wavelength near the size of the beam spot and the response fall correlate to surface wavelength.
- 2) We confirmed that we could improve the accuracy of the comparison between the instruments with different principles when we unify the range of objective wavelength under analysis by the introduction of a transmission filter. It is important to examine the response properties of the measuring instruments against the surface wavelength.

ACKNOWLEDGMENT

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VACUUM SUPPORT FOR A LARGE INTERFEROMETRIC REFERENCE SURFACE

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OVERVIEW

This paper presents a vacuum support technique for a Fizeau type interferometer that uses a 1.1 m diameter reference surface. The interferometer uses Computer Generated Holograms (CGHs) for aspheric measurement, illumination optics and imaging optics. To reduce the effects of air turbulence and retrace error, the gap between the reference surface and Unit Under Test (UUT) is limited to 5 mm. The illumination optics consist of two lenses, one of which we call the test plate which includes the reference surface. The 1.1-m diameter illumination optics are quite heavy, 212 kg, and are prone to self-weight deflection problems. We solve this with a vacuum support of the test plate. A vacuum region is created between the two lenses in the illumination optics using a rubber seal. The upper lens of the illumination optics suffers extra deflection caused by vacuum. However, since this lens is in the common path of the interferometer this does not cause significant error in the interferogram.

In this paper, a simple experiment on a small surface and analyses on a large model are discussed. In the simple experiment the deflection of flat surfaces having 100mm in diameter and 2.7mm in thickness was measured by a Wyko 6000 interferometer. The region between the two flat surfaces was sealed by an O-ring and a needle was inserted into the O-ring so that the sealed region could be evacuated. This experiment shows correspondence of less than 10 % between the simulation and the experiment. A finite element model simulation of the vacuum support for the 1.1-m test plate is also presented. The nominal surface slope irregularity caused by gravity at the reference surface is 26.88 nm/cm RMS. When a differential pressure is equal to 2300 Pa, the deflection is minimized to 0.75 nm/cm RMS. Based on an optical simulation of the system, this deflection introduces only 8.0 nm RMS into the measurement error. Therefore the vacuum

support can be useful for reducing the effect of gravity on the reference surface.

INTRODUCTION

Large convex and flat optics are accurately and efficiently measured using Fizeau interferometry, where the reference optic may be a meter or larger in diameter. The self-weight deflection of the reference optic must be considered. Any unknown shape change will cause an error in the measurement. Even a shape change that is well known will affect the measurement by increasing the dynamic range. It is possible to polish the inverse of the deflection into the optic so that the gravity effect is canceled, but this is difficult to do in practice.

M. B. Dubin et al. designed a Fizeau type interferometer to measure a secondary mirror for a telescope as shown in Figure 1^[1].

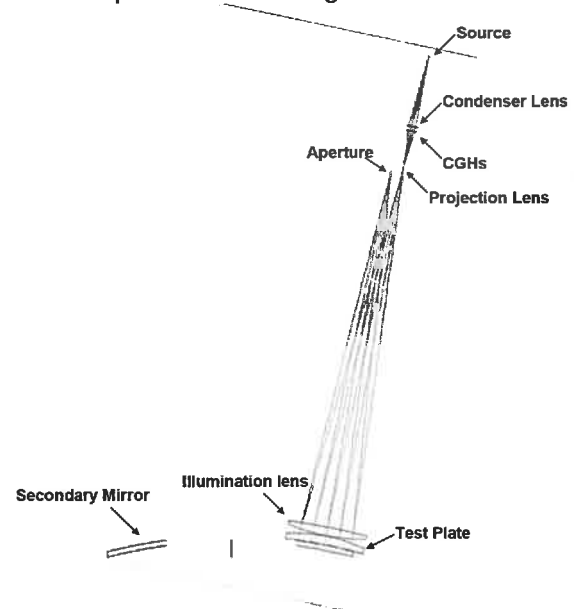


FIGURE 1. A Fizeau type interferometer having 1.1-m diameter reference surface measures a secondary mirror for a telescope.

In this case, the test plate including a reference surface would be bent because of the gravity. It

becomes a problem, since the test plate itself would be flipped around after polishing the reference surface. Reducing the unexpected bending in the reference surface is required. For this purpose, evacuating air between the test plate and the illumination lens can be useful and effective for compensating the bending caused by the gravity.

REQUIREMENTS

Requirements for the vacuum support are listed in Table 1.

TABLE 1. Requirements and Verifications for the vacuum support.

	Requirement		Verification
1.	Difference between simulation and experiment	< 20 %	Test
2.	Supported by the edge face	NA	Inspection
3.	Surface slope irregularity	< 10 nm/cm RMS	Analysis
4.	Resonant Frequency	> 30 Hz	Analysis
5.	Stability - Power - w/o Power	20 [nm] 3 [nm]	Analysis

The second requirement of "Supported by the edge" means that the test plate should be supported along the outer circumference, because there is not enough space under the test plate.

EXPERIMENT

Experimental Setup

This section validates the first requirement of difference between simulation and experiment is less than 20 % by a simple experiment.

Two flat surfaces made by Valley Design Corp. were used for this experiment. The flat surfaces were made from Borofloat, 100 mm in diameter, 2.69 mm in thickness, standard polished finish, and 60/40 scratch/dig. The surface flatness was measured by Unilamp made by Midwest Scientific Co. There were about 10 fringes on the flat surfaces.

A schematic of the vacuum system is shown in Figure 2 and the actual system is shown in

Figure 3. The needle inserted into the O-ring connects to the vacuum system consisted of a vacuum pump, a reservoir, a leak valve, and a pressure gage.

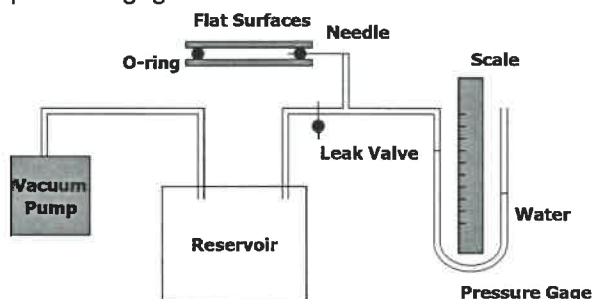


FIGURE 2. A schematic vacuum system for the simple experiments.

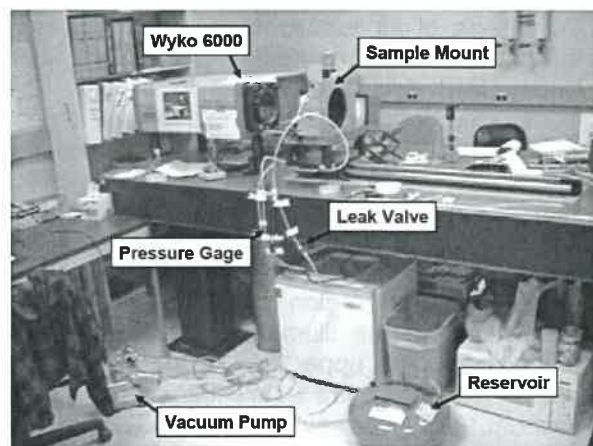


FIGURE 3. The actual vacuum system for the simple experiments.

The pressure gage consists of just a tube filled with water and a scale so that a sensitive vacuum level measurement can be achieved in low cost. In this experiment, a sensitivity required in the pressure gage was relatively tight because a little pressure change can affect the interferogram easily. Also, the pressure should be measured relative to atmosphere or ambient pressure. Then, a water height gage was chosen. Since 1 atmosphere is equivalent to 10.3 m in water height, the height of 101.7 mm is changed in 1000 Pa.

The flat and simply supported surface deflection caused by uniform loading can be calculated by using the following equation.

$$\delta_{\max}(P) = C_D \left(\frac{P}{E} \right) \frac{r^4}{h^3} (1 - \nu^2) \cos \theta$$

$\delta_{\max}$ is the maximum surface deflection, C_D is the deflection constant, P is the pressure, E is the elastic modulus, r is the radius of the evacuated

area, h is the thickness of the flat surface, ν is the Poisson's ratio, and θ is the angle between the optical axis and local vertical. In this experiment, $C_D = 0.828$ (Edge simply supported) for the O-ring, $E = 64$ GPa, $\nu = 0.2$ for Borofloat glass, $r = 43.125$ mm, $h = 2.69$ mm, and $\theta = 0$. When $P = 1000$ Pa, the maximum deflection $\delta_{\max}$ becomes $2.21 \mu\text{m}$. $2.21 \mu\text{m}$ is enough to obtain reasonable accuracy with the interferometer. Thus our target of vacuum level for the system was 1000 Pa.

The flat surfaces were set in front of Wyko 6000 interferometer as shown in Figure 4.

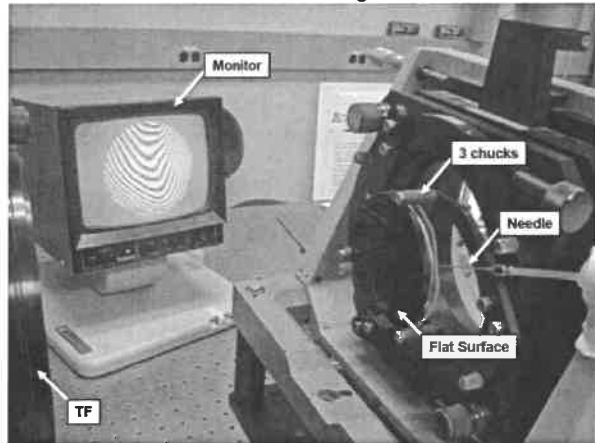


FIGURE 4. Flat surface is mounted in front of the interferometer.

A region between two flat surfaces was sealed by an O-ring similar to E. Everhart's method^[2]. A needle was inserted into the O-ring so that the sealed region could be evacuated. The diameter of the O-ring was 86.25 mm and the thickness was 5.6 mm, and the diameter of the needle is 1.06 mm. The O-ring and the two flat surfaces were glued by RTV157 to prevent leaking from the small cavity between them. The back surface of the flat surface measured by an interferometer was coated by #33 Liquid made by Universal Shellac & Supply company, Inc. to avoid a reflection from the back surface affecting the interferogram.

Experimental Results

Figure 5 shows the relationship between pressure and Power term (Zernike 4th term (Z_4)) for both the experimental data and simulation data. The experimental data is shown in solid line with error bars and simulation data is shown in dashed line. The relationship between pressure and Power term (Z_4) is linear with as ratio of $5.82\text{E-}4 \mu\text{m}/\text{Pa}$ in the experiment and

$5.87\text{E-}4 \mu\text{m}/\text{Pa}$ in the simulation. In the experimental data, the solid line connects the average points calculated by 3 same pressures. Also, each data points have error bars calculated from the 3 same pressures. Figure 5 shows the excellent correspondence between the experimental data and the simulation data in this region. The maximum difference between experiment and simulation is 9.6 % at 275 Pa. As G. Lemaitre mentioned, p^4 term (Zernike 11th term (Z_{11})) was also appeared as shown in Figure 6^[3]. The maximum difference between experiment and simulation is 9.9 % at 275 Pa. This experiment shows correspondence of less than 10 % between a simulation and an experiment, which meets the requirement of 20 %.

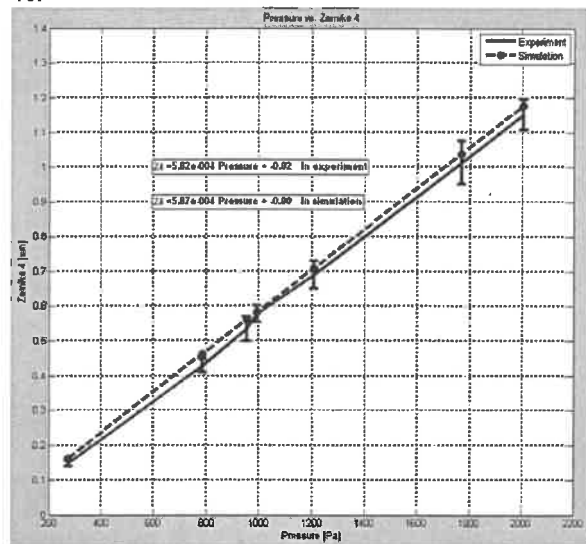


FIGURE 5. Pressure vs. Zernike 4th term.

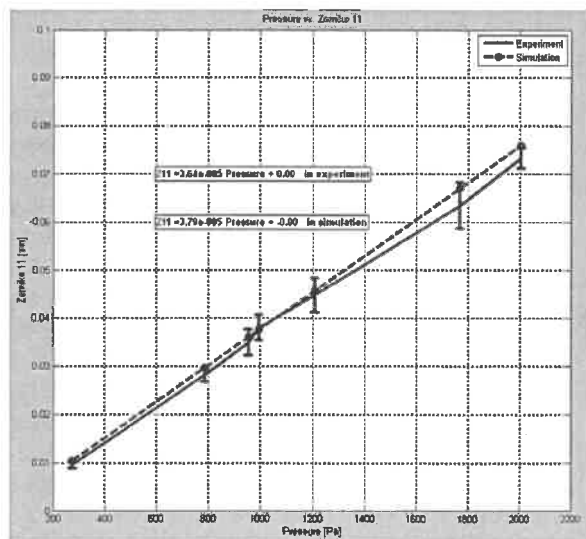


FIGURE 6. Pressure vs. Zernike 11th term.

ANAYSIS

Design Concept

Figure 7 shows a design concept for the 1.1-m diameter test plate. Three 2-axis flexures support the test plate laterally, and three hard contacts support the test plate axially. The 2-axis flexure is connected to the test plate via Invar parts. The Invar parts are intermediate parts to prevent stress caused by a difference of thermal expansion coefficients of the test plate and the flexures. The three hard contacts are located on the flange of the test plate. This flexure system allows the test plate to be compliant in lateral direction and stiff in axial direction. In addition, the hard contacts are used to measure the pressure required to support the test plate with load cells.

As Figure 7 shows, the test plate is supported along the outer circumference, because there is not enough space under the test plate. This meets the second requirement.

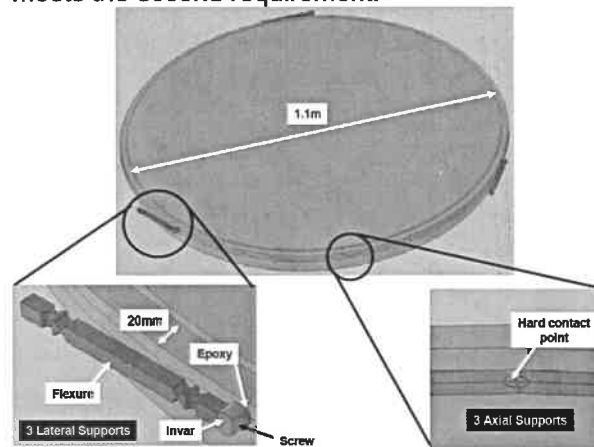


FIGURE 7. The test plate is supported by three flexures and three hard contacts along to outer circumferential.

Figure 8 shows a schematic of the hard contact. The test plate has the flange around the edge surface, which has 20 mm in radial direction and 20 mm in axial direction. There are three load cells, part number LLB300 made by Futek Advanced Sensor Technology Inc. The maximum load capacity is 500 lbs. (227 kg) and nonlinearity is 0.5 %. These three load cells are located under the flange of the test plate to measure the actual lens weight. When the test plate is supported by vacuum, the lens's weight is changed based on the pressure level. Since it is difficult to measure in-situ vacuum pressure precisely, the load cells are used instead of a pressure gauge. Also, by measuring the lens's

weight at three different points, non-uniformity of a sealing, such as tilt, will be known.

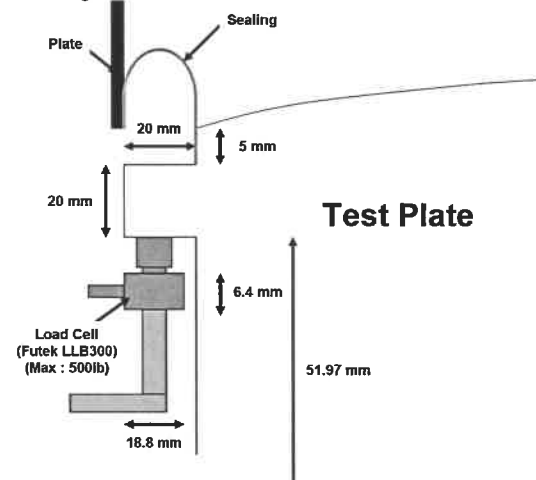


FIGURE 8. A schematic of Hard contact and Load cell.

Surface Slope Irregularity

A relationship between pressure and surface slope irregularity of the test plate was simulated including a seal. This means that gravity, pressure on the reference surface of the test plate, and force on edge of the test plate caused by vacuum were applied to the simulation of surface slope irregularity. A cross section diagram regarding the sealing effect is shown in Figure 9.

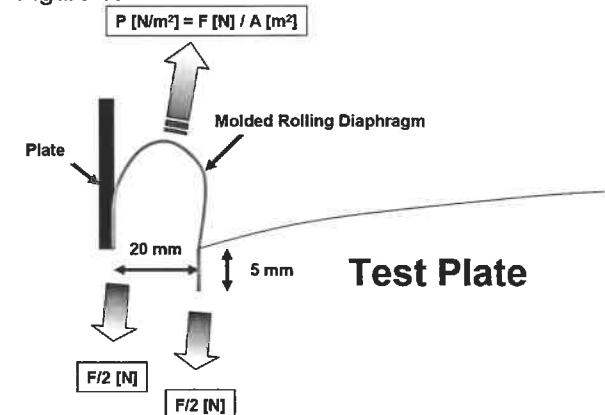


FIGURE 9. A schematic of Sealing effect.

The evacuated area is sealed by a plate and a molded rolling diaphragm. Since the plate can be considered as a rigid part, it is not bent by vacuum. But, the molded rolling diaphragm is bent by vacuum as shown in Figure 9. The reason why the shape of the sealing material is like an inverse of "U" is to allow the test plate move laterally and axially. Above pressure caused by vacuum creates below forces in

Figure 9. A force on the test plate is half of the force caused by vacuum basically. Because of choosing the molded rolling diaphragm, the force on the test plate is almost parallel to the optical axis. The difference between the surface slope irregularity with the force on the test plate and without the force is only 0.13 nm/cm RMS at 2300 Pa. Then, the amount and direction of the force on the test plate does not affect the surface slope irregularity.

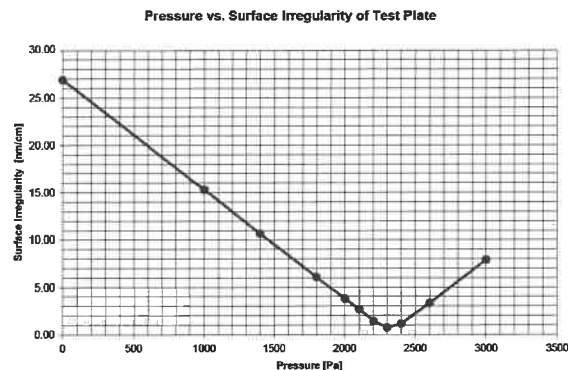


FIGURE 10. Pressure vs. Surface slope irregularity.

Figure 10 shows the relationship between pressure and surface slope irregularity when the sealing effect is considered. When the area between the test plate and the illumination lens is evacuated to 2300 Pa, the surface slope irregularity is minimized to 0.75 nm/cm RMS. When pressure is equal to 2300 Pa, the force on the test plate caused by the sealing is 80.3 N.

Figure 11 shows the interferograms of the system without the vacuum support and with the vacuum support. The vacuum support can reduce an error from 86.5 nm RMS to 8.0 nm RMS.

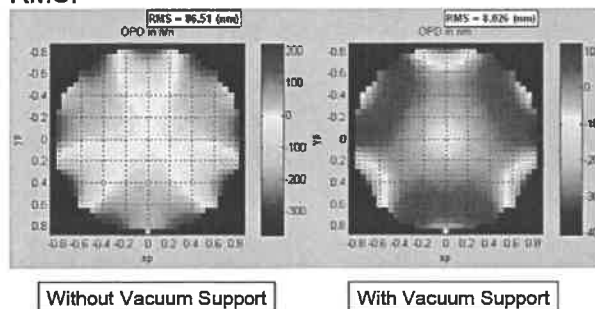


FIGURE 11. Interferograms of the system without the vacuum support and with the vacuum support.

When the test plate has a decenter of 100 μm , the area of the sealing material, which should be

taken into account to calculate the force on the test plate, changes. This means that the force on the test plate also changes about 0.4 N. However, the change of the surface slope irregularity is only 0.02 nm/cm RMS in the case of 0.4 N, then the decenter of the test plate does not affect the surface slope irregularity.

Next, moments caused by flexure supporting the test plate laterally was considered. This effect is not dependent from vacuum level. When the flexures are attached to the test plate or other mechanical components, there are appropriate tolerances. Since these tolerances make the flexures bend and distort, then these bending and distortion create moment on the attached surface of the test plate.

In the case of the flexure shown in Figure 7, a tolerance of 96 μm causes a torque of 0.2 N-m. When a flexure has a torque of 0.2 N-m, the simulated deflection is shown in Figure 12.

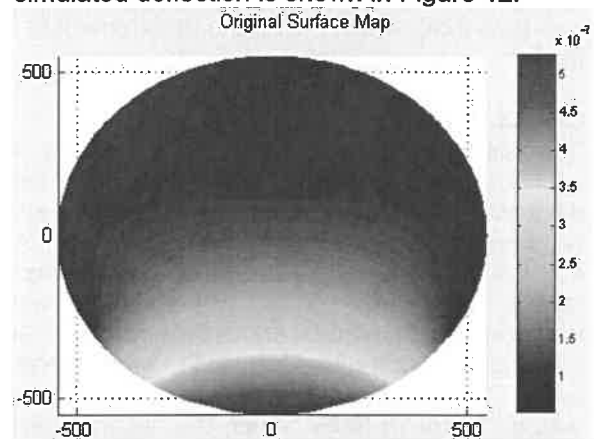


FIGURE 12. Simulated deflection is shown when a flexure has a torque of 0.2 N-m.

The surface slope irregularity is 2.71 nm/cm RMS. Since the surface slope irregularity can be summed up by root sum square (RSS), the surface slope irregularity with three tolerated flexure becomes 4.69 nm/cm. When the original surface slope irregularity of 0.75 nm/cm RMS is considered, the total RSS becomes 4.75 nm/cm RMS, which met the requirement of 10 nm/cm RMS.

Resonant Frequency

The 1st resonant frequency of this system was 242.1 Hz, which meets the requirement of 30 Hz. For bonding the test plate and invar joints, Epoxy of Scotch-Weld EC-2216 made by 3M was used. But stiffness of Epoxy does not affect the resonant frequency, because the system uses hard contacts and then the dominant term

defining a resonant frequency is stiffness and mass of the test plate itself.

Stability

The Load Cell has a Non-Linearity of 0.5 % for an output signal. When 2300 Pa is applied to the test plate, the stability of the system is 11.5 Pa. The difference between the deflection patterns of 2300 [Pa] and 2311.5 [Pa] was simulated via Power term (Z4) and the other terms without Piston (Z1), Tilt (Z2 and Z3), and Power term (Z4). Since Power term (Z4) at 2300 [Pa] was 11.37 [nm] and Power terms (Z4) at 2311.5 [Pa] was 9.03 [nm], then the Power terms difference between 2300 [Pa] and 2311.5 [Pa] was 2.34 [nm], which meets the requirement of 20 [nm]. Since the other terms without Piston (Z1), Tilt (Z2 and Z3), and Power term (Z4) at 2300 [Pa] was 8.16 [nm] and the other terms at 2311.5 [Pa] was 8.54 [nm], then the other terms difference between 2300 [Pa] and 2311.5 [Pa] was 0.38 [nm], which meets the requirement of 3 [nm].

CONCLUSION

The simple experiment and analyses for a vacuum support were studied. The maximum difference between experimental data and simulation data was 9.6 [%] in Power term (Z4) and 9.9 [%] in p^4 term (Z11) at 275 [Pa], which met a requirement of 20 [%]. Then, it was validated that simulation about deflection caused by vacuum corresponded with experimental data. The simulated surface slope irregularity was 0.75 nm/cm RMS. When the flexures have a moment, the RSS of the surface slope irregularity including the original 0.75 nm/cm and moment effect was 4.75 nm/cm RMS, which met the requirement of 10 nm/cm RMS. The simulated resonant frequency was 242.1 [Hz], which met a requirement of more than 30 [Hz]. For stability, the Power term (Z4) stability was 2.34 [nm], which meets the requirement of 20 [nm], and the stability of the other terms without Piston (Z1), Tilt (Z2 and Z3), and Power term (Z4) was 0.38 [nm], which meets the requirement of 3 [nm]. Therefore, all requirements are met by the experimental results and analyses and the vacuum support can be useful for reducing errors in the reference surface.

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ULTRA-PRECISION LINEAR MOTION METROLOGY

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ABSTRACT

Many new emerging applications of nanotechnologies require the use of compact precision linear translation stages that have positioning resolution on the order of a nanometer and an exceptionally long range of motion on the order of tens of millimeters. Such devices are expected to perform with sub-micrometer positioning accuracy and repeatability. Manufacturers and consumers of such systems have begun to recognize the difficulties in certifying the performance of these systems with appropriate levels of measurement uncertainty. Sources of measurement uncertainty that were once considered insignificant when measuring in the micrometer regime are now very significant when measuring in the nanometer regime. This paper describes the work being performed to investigate and evaluate the use of interferometry for measuring and determining the accuracy and repeatability of positioning numerically-controlled axes with levels of uncertainty of a few nanometers or better.

INTRODUCTION

For many years, the geometric accuracy and repeatability of positioning numerically-controlled machine axes have been characterized using the measurement guidelines and analyses outlined by national and international standards [1,2]. The most popular instrument for performing these measurements has been the displacement measuring interferometer (DMI), consisting of a stabilized laser source with a nominal wavelength of 633 nm, interferometer optics, retroreflector, and a weather station used for correcting the laser wavelength for changes in the refractive index of air and for correcting displacement errors caused by thermal expansion of the linear axis. Measurements of traditional machine tool axes with specified

positioning accuracies and repeatabilities on the order of tens of micrometers have been made using DMI systems because uncertainty in DMI measurements have been at best an order of magnitude better than the reported specifications. However, many new ultra-precision machine tools and instruments use ultra-precision linear positioning systems with resolutions on the order of a nanometer coupled with exceptionally long ranges of motion (tens of millimeters) requiring sub-micrometer positioning accuracy and repeatability. A few applications include, semiconductor wafer inspection, micro/meso-machining, and photonic alignment, to name a few.

Such systems, mostly made of aluminum structures, are compact with heights ranging from 20 mm to 72 mm and widths ranging from 90 mm to 230 mm, and offer linear travels ranging from 20 mm to 160 mm with resolutions from 1 nm to 5 nm. In general, positioning is achieved with direct-drive, non-contact linear motors, high resolution linear encoders, and precision control. Performance specifications provided for these systems vary with accuracies ranging from 250 nm to 5 μ m, bidirectional repeatabilities ranging from 50 nm to 200 nm, unidirectional repeatabilities ranging from 25 nm to 100 nm, and angular errors (pitch & yaw) ranging from 5 arc seconds to 20 arc seconds.

Measuring and certifying the linear positioning performance of this class of linear positioning system with DMI will be very challenging if the test uncertainty ratio (TUR) is to be greater or equal to 4:1 as indicated in [3]. For example, a measurement of the unidirectional repeatability with a specification of ± 25 nm will require an expanded measurement uncertainty, U , of approximately 6 nm or less. Assuming a 95 % level of confidence in the measurement, where

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$U = 2u_c$ (i.e., the coverage factor, k , equals 2), will require a combined standard uncertainty, u_c , of approximately 3 nm or less.

To address the challenges for characterizing such systems with appropriate measurement uncertainties, we started an effort to extend our linear displacement measurement capabilities for this operational regime. A preliminary uncertainty analysis was performed to estimate the measurement uncertainty in characterizing a typical ultra-precision translation stage with our planned measurement system. The positioning system performance specifications used for this analysis are given in Table 1. Existing international standards [2,4] and the Guide to the Expression of Uncertainty in Measurement (GUM) [5] were used as guidelines for this uncertainty analysis.

TABLE 1. General Performance Specifications

Specification	Value	Unit
Travel	50	mm
Accuracy	± 250	nm
Resolution	1	nm
Bi-direct Repeat	± 50	nm
Uni-direct Repeat	± 25	nm
Pitch/Yaw	± 10	arc sec
Material	Al	-----

MEASUREMENT SETUP

Linear positioning measurements will take place on top of a passive vibration isolation table located in an environmentally controlled laboratory where the temperature is controlled to $20^\circ\text{C} \pm 0.1^\circ\text{C}$. The measurement system currently being assembled is a single-pass heterodyne DMI consisting of a laser source, beam splitter, and retroreflector. A commercially available Helium-Neon dual frequency 20 MHz laser with a nominal laser wavelength of 633 nm and wavelength accuracy of 0.1 parts per million (ppm) is used as the laser source. Reference and measurement signals from the interferometer will be captured by fiber optic couplings and transmitted via fiber optic cables to a measurement board where displacement will be determined with a resolution of 0.62 nm.

The linear positioning stage and the interferometer optics will be connected through an alignment sled manufactured from Invar, shown in Fig. 1. The sled, positioned against a guide rail, will be used for speeding up the coarse alignment of the laser beam and stage

by allowing the operator to slide the sled the entire length of the rail while adjusting the laser. The sled will also be used to reduce both the thermal and measurement loops. Precision alignment of the laser beam and stage travel will be achieved using a combination of precision adjusters mounted to the laser and a beam position sensing detector (PSD) with an accuracy of approximately ± 0.03 mm.

Changes in the laser wavelength due to changes of the refractive index of the surrounding air will be automatically compensated during the measurement process. At startup, the refractive index of air will be determined using Edlen's equation [6,7] and by measuring temperature, barometric pressure, and relative humidity with a thermistor, pressure transducer, and humidity sensor with accuracies of $\pm 0.005^\circ\text{C}$, ± 16 Pa, and $\pm 2\%$, respectively. Changes in the refractive index of air will then be tracked using a commercially available wavelength compensator (refractometer) that can detect a 1.1×10^{-9} change in refractive index. Material temperature changes in the sled and stage will be monitored using surface mount thermistors, each having a measurement accuracy of $\pm 0.1^\circ\text{C}$. Each environmental sensor will be positioned as close to the measurement path as possible to most accurately measure environmental changes occurring within the measurement loop. The operator will monitor and control the measurement process through a graphical user interface and personal computer.

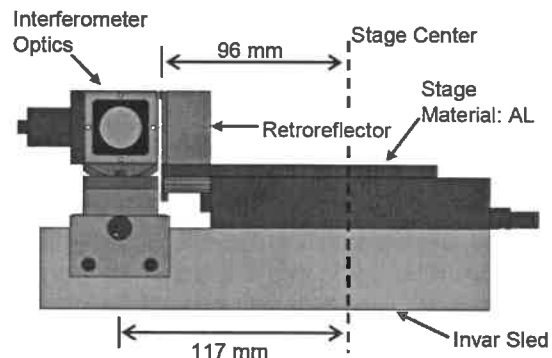


FIGURE 1. Measurement Setup

UNCERTAINTY ANALYSIS

Multiple sources of error contribute to the uncertainty in measurement when measuring the performance of an ultra-precision axis. In

this analysis, each error source is assumed to be uncorrelated and to have a rectangular probability distribution. Each one is estimated assuming that its respective error value lies within a possible range of $\pm a$ or $(a^+ - a^-)$. The standard uncertainty, u_i , associated with each error source is described by Eq. 1.

$$u_i = \frac{a^+ - a^-}{2\sqrt{3}} \quad (1)$$

The uncertainties due to the individual error sources are combined according to Eq. 2.

$$u_c = \sqrt{\sum_i u_i^2} \quad (2)$$

Unidirectional repeatability, $R_i \uparrow$, for positioning an axis at a position, x_i , is described by Eq. 3.

$$R_i \uparrow = 4 \cdot s_i \uparrow \quad (3)$$

where s_i is the standard deviation of the measurement values, x_{ij} , recorded at position x_i by a series of N unidirectional approaches ($N = 5$) and 4 represents the range of the data for a coverage factor of 2, i.e. $\pm 2s_i$. As described by Eq. 4, the unidirectional repeatability for an entire axis is the maximum repeatability value of all positions.

$$R \uparrow = \max(R_i \uparrow) \quad (4)$$

The uncertainty for the unidirectional repeatability is four times the uncertainty of the standard deviation, $u(s)$ in positioning and is described by Eq. 5.

$$u(R \uparrow) = 4 \cdot u(s \uparrow) = 4 \cdot u_x \sqrt{\frac{1}{N-1}} = \dots \quad (5)$$

$$4 \cdot \sqrt{\frac{1}{N-1}} \cdot u_{EVE}$$

where u_x is the uncertainty in positioning with the only contributor being the uncertainty due to the environmental variation error, u_{EVE} . Bidirectional repeatability, R , for an axis is the maximum of the bidirectional repeatability values, R_i , described by Eq. 6.

$$R_i = \max[2s_i \uparrow + 2s_i \downarrow + |B_i|; R_i \uparrow; R_i \downarrow] \quad (6)$$

where B_i is the reversal value at a position. The uncertainty for bidirectional repeatability is described by Eq. 7.

$$u(R) = \sqrt{u(B)^2 + u(R \uparrow, R \downarrow)^2} \quad (7)$$

where $u(B)$ is the uncertainty in the reversal value described by Eq. 8.

$$u(B) = 2 \cdot \sqrt{\frac{u_{EVE}^2}{N} + u_{SETUP}^2} \quad (8)$$

where u_{SETUP} is the uncertainty due to the repeatability of the measurement setup. The

accuracy, A , for a bidirectional measurement of positioning an axis is determined by Eq. 9 and the uncertainty for the accuracy measurement is determined by Eq. 10.

$$A = \max[\bar{x}_i \uparrow + 2s_i \uparrow; \bar{x}_i \downarrow + 2s_i \downarrow] - \dots \quad (9)$$

$$\min[\bar{x}_i \uparrow - 2s_i \uparrow; \bar{x}_i \downarrow - 2s_i \downarrow]$$

$$u(A) = \sqrt{u(E)^2 + u(R \uparrow, R \downarrow)^2} \quad (10)$$

where $\bar{x}_i$ is the arithmetic mean of the positional deviations and $u(E)$ is the uncertainty due to the bidirectional systematic positional deviation described by Eq. 11

$$u(E) = \sqrt{u_{DEVICE}^2 + u_{MISALIGNMENT}^2 + u_{SETUP}^2 + \frac{u_{EVE}^2}{n}} \quad (11)$$

where u_{DEVICE} is the uncertainty due to the measuring device, and $u_{MISALIGNMENT}$ is the uncertainty due to misalignment of the measuring device and the axis of travel.

Measurement Device Uncertainty

Uncertainty due to the measuring device is described by Eq. 12.

$$u_{DEVICE} = \sqrt{u_{\lambda}^2 + u_{M,n}^2 + u_{DP}^2 + u_{DR}^2} \quad (12)$$

where u_{λ} is the uncertainty due to laser wavelength accuracy, $u_{M,n}$ is the uncertainty in correcting for changes in laser wavelength due to changes in the refractive index of air, u_{DP} is the uncertainty due to the dead-path error, and u_{DR} is the uncertainty due to the device resolution. For this application the dead-path distance is assumed to be negligible and u_{DP} is set to zero. The laser head used has a specified lifetime wavelength accuracy, λ_A , equal to ± 0.1 ppm and the resolution, r , provided by the measurement board is 0.62 nm. Uncertainty due to laser wavelength accuracy is described by Eq. 13.

$$u_{\lambda} = \frac{L \cdot (\lambda_A - \lambda_A)}{2\sqrt{3}} = 2.9 \text{ nm} \quad (13)$$

where L is the measurement length and is set to the maximum travel of the stage, i.e. $L = 50$ mm. Device resolution uncertainty is determined by Eq. 14.

$$u_{DR} = \frac{r}{2\sqrt{3}} = 0.2 \text{ nm} \quad (14)$$

The uncertainty in correcting for changes in the refractive index of air is described by Eq. 15.

$$u_{M,n} = u_n \cdot L \quad (15)$$

where u_n is the uncertainty in determining the refractive index of air. The refractive index of air, n , as described by Edlen's equation [6], is a

function of the ambient air temperature, barometric pressure, and relative humidity and the uncertainty in determining the refractive index of air can be described by Eq. 16.

$$u_n = \sqrt{\left(\frac{\partial n}{\partial T}\right)^2 u_{TD}^2 + \left(\frac{\partial n}{\partial P}\right)^2 u_{PT}^2 + \left(\frac{\partial n}{\partial H}\right)^2 u_{RHS}^2} \quad (16)$$

where u_{TD} , u_{PT} and u_{RHS} are the uncertainties in measuring air temperature, barometric pressure, and relative humidity and are equal to 0.003 °C, 9.3 Pa, and 1.2 %, respectively. For this application, the uncertainty of the refractive index is estimated to be 0.027×10^{-6} resulting in a measurement correction uncertainty at maximum travel of 1.4 nm. The resulting combined uncertainty for the measuring device, u_{DEVICE} , is estimated to be 3.2 nm.

Alignment Uncertainty

Misalignment between the laser beam and the direction of travel of the stage axis (out of parallelism) can cause an error in the displacement measurement. The standard uncertainty due to misalignment is estimated by Eq. 17.

$$u_{MISALIGNMENT} = \frac{L \cdot (1 - \cos \gamma)}{2\sqrt{3}} \quad (17)$$

where γ is the angle of misalignment determined by Eq. 18.

$$\gamma = \sin^{-1} \frac{\Delta h}{L} \quad (18)$$

where Δh is the maximum beam deviation at full travel equal to ± 0.03 mm. The resulting alignment angle is approximately 124 arc seconds resulting in a maximum standard uncertainty due to misalignment of 2.6 nm.

Measurement Setup Uncertainty

Positioning accuracy and repeatability will vary between different lines of measurement if the axis being measured possesses pitch and/or yaw characteristics. If the measurement data is used for calculating the volumetric accuracy, for compensation purposes, or if the measurement is repeated for verification of performance certification, then the setup error influences the measurement length. To minimize this effect, sound precision engineering practices employing minimum constraint design and precision mechanical alignment techniques will be used to appropriately assemble each measurement setup and ensure a low variability in lines of measurement. The standard uncertainty associated with the measurement setup, u_{SETUP} , is described by Eq. 19.

$$u_{SETUP} = \frac{\sqrt{2} \cdot O_{ABBE} \cdot D_{ANGLE}}{1000 \cdot 2\sqrt{3}} \quad (19)$$

where O_{ABBE} is the estimated maximum change in Abbe offset between two possible lines of measurement in millimeters and D_{ANGLE} is the maximum angular error of the axis being measured in micrometers per meter. The maximum angular deviation of the stage is obtained from Table 1 as 10 arc seconds (48.5 $\mu\text{m/m}$) and it is assumed that the maximum change in Abbe offset will be no more than 0.1 mm. The standard uncertainty resulting from the measurement setup and the angular characteristics of the stage is estimated to be 2.0 nm.

Environmental Variation Error Uncertainty

During the time it takes to perform the measurement, the measurement setup and/or environment may drift causing a measurement error known as environmental variation error (E_{VE}). E_{VE} is taken as the range of the data recorded while performing a drift test with the stage carriage held at the maximum travel position. Presently, the complete experimental setup exists only in a virtual (design) state making it impossible to perform a drift test. For this reason, the environmental variation error is estimated by estimating the effects caused by thermal expansion of the experimental setup. The linear positioning measurement process will be relatively slow with the stage coming to rest at each measurement position. It is assumed that the temperature of the experimental setup will not vary more than the temperature swing of the lab and any changes in position measurement during the drift test will be due to the temperature swing of the lab. In this analysis, it is assumed that the stage and the interferometer optics are attached to the Invar sled at their respective centers, see Fig. 1, and are allowed to thermally expand from center. The retroreflector is attached to the end of the carriage. It is also assumed that the stage zero position or the placement of the encoder read head is located at the center of the stage base. E_{VE} is estimated as the difference in the change in position of the interferometer optics and retroreflector after a maximum temperature swing, ΔT , of 0.1 °C and is described by Eq. 20.

$$E_{VE} = (\alpha_{AL} d_1 - \alpha_{INVAR} d_2) \cdot \Delta T = 211 \text{ nm} \quad (20)$$

where d_1 and d_2 are the distances from stage center to the optical components and α_{AL} and α_{INVAR} are the coefficients of thermal expansion of the stage and sled material, i.e., $\alpha_{AL} =$

23.6 $\mu\text{m}/\text{m}\cdot^\circ\text{C}$ and $\alpha_{\text{INVAR}} = 1.3 \mu\text{m}/\text{m}\cdot^\circ\text{C}$. Thermal growth of the optical components is ignored in this estimate. The standard uncertainty due to E_{VE} is described by Eq. 21.

$$u_{EVE} = \frac{E_{VE}}{2\sqrt{3}} = 122 \text{ nm} \quad (21)$$

Because the uncertainty due to E_{VE} is relatively large when compared to the desired uncertainty for unidirectional repeatability, the measurement data will be automatically compensated for changes in thermal growth of the setup. Therefore, the standard uncertainties of the material temperature measurements, $u_{TM,i}$, and the thermal expansion coefficients, $u_{EM,i}$, must be considered. The uncertainty due to the temperature measurement of the material (in this estimate the ambient air) is given by Eq. 22.

$$u_{TM,i} = \alpha_i \cdot d_i \cdot u(\Theta) \quad (22)$$

where $u(\Theta)$ is the standard uncertainty due to the temperature measuring device and is equal to 0.003 $^\circ\text{C}$. The resulting uncertainties due to temperature measurements of the sled, $u_{TM,\text{INVAR}}$, and carriage, $u_{TM,\text{AL}}$, are 0.5 nm and 6.8 nm, respectively. The standard uncertainty due to the material coefficient of thermal expansion is described by Eq. 23.

$$u_{EM,i} = \Delta T \cdot d_i \cdot u(\alpha_i) \quad (23)$$

where $u(\alpha_i)$ is the uncertainty of the material expansion coefficient and is estimated by assuming a minimum range of 10% of the nominal value and is transferred to a standard deviation according to Eq. 24.

$$u(\alpha_i) = \frac{0.1 \cdot \alpha_i}{2\sqrt{3}} \quad (24)$$

$u(\alpha_{\text{INVAR}})$ and $u(\alpha_{\text{AL}})$ are 0.04 $\mu\text{m}/\text{m}\cdot^\circ\text{C}$ and 0.68 $\mu\text{m}/\text{m}\cdot^\circ\text{C}$, respectively, resulting in standard uncertainties due to the material expansion coefficients $u_{EM,\text{INVAR}}$ and $u_{EM,\text{AL}}$ of 0.4 nm and 6.5 nm, respectively. The standard uncertainty due to E_{VE} is now equal to the standard uncertainty due to the compensation of the material temperatures and is described by Eq. 25.

$$u_{EVE} = \sqrt{u_{TM,\text{INVAR}}^2 + u_{EM,\text{INVAR}}^2 + \dots + u_{TM,\text{AL}}^2 + u_{EM,\text{AL}}^2} = 9.3 \text{ nm} \quad (25)$$

UNCERTAINTY RESULTS

The resulting combined standard and expanded uncertainties for the performance parameters are listed in Table 2 and the uncertainty

estimates for each contributor are listed in Table 3.

TABLE 2. Uncertainty Estimates for the Performance Parameters

Parameter	$u(i)$	$U(i) (k=2)$	Unit
$R_i \uparrow$	18.5	37	nm
B	9.2	18.3	nm
R	20.6	41	nm
E	6	12	nm
A	19.5	39	nm

TABLE 3. Uncertainty Contributors Estimates

Contributor	Value	Unit
u_λ	2.9	nm
u_{TD}	0.005	$^\circ\text{C}$
u_{PT}	16	Pa
u_{RHS}	2	%
u_n	0.027	ppm
$u_{M,n}$	1.4	nm
u_{DP}	0	nm
u_{DR}	0.1	nm
u_{DEVICE}	3.2	nm
$u_{MISALIGNMENT}$	2.6	nm
u_{SETUP}	2.0	nm
$u(\Theta)$	0.003	$^\circ\text{C}$
$u_{TM,\text{INVAR}}$	0.5	nm
$u_{TM,\text{AL}}$	6.8	nm
$u(\alpha_{\text{INVAR}})$	0.04	$\mu\text{m}/\text{m}\cdot^\circ\text{C}$
$u(\alpha_{\text{AL}})$	0.68	$\mu\text{m}/\text{m}\cdot^\circ\text{C}$
$u_{EM,\text{INVAR}}$	0.4	nm
$u_{EM,\text{AL}}$	6.5	nm
u_{EVE}	9.3	nm

DISCUSSION OF RESULTS

The results from this analysis clearly highlight the challenges in measuring the performance of this class of linear positioning system with a TUR of 4:1 using our current measurement system. The expanded uncertainty in measuring the unidirectional repeatability exceeds the performance specification of 25 nm by a factor of 1.5 and the expanded uncertainty in bidirectional repeatability is approximately equal to the specified performance of 50 nm producing a TUR of 1:1. The largest contributor to the measurement uncertainty in this analysis is the uncertainty in compensating for the environmental variation error ($u_{EVE} = 9.3 \text{ nm}$). However, this analysis is based on the assumption that the temperature of the experimental setup will only change with room temperature. If heat, caused by bearing friction, the motor, or other sources, is added to the

stage causing the stage temperature to vary more than the temperature of the lab then the previous assumption will be false. In this case, the analysis for the uncertainty due to the bidirectional systematic positional deviation, $u(E)$, will need to also include the uncertainty due to machine temperature compensation, u_T , and the uncertainty of the surface mount thermistors. To provide an example of the significance of u_T as a contributor to the measurement uncertainty, we will assume the stage temperature varies by at least 1 °C from 20 °C. In this case, the contribution to the standard measurement uncertainty will be approximately 150 nm.

One method for reducing the measurement uncertainty may include replacing the existing laser source and environmental sensors with products that have better specified accuracies and/or uncertainties. For example, this may include replacing the existing laser with an iodine stabilized laser source that has a wavelength accuracy better than 1 part in 10^{10} . Doing so would further reduce the uncertainty due to wavelength accuracy to a level well below a nanometer which would, in-turn, reduce the device uncertainty to 1.4 nm or better.

Another method for lowering the measurement uncertainty may include the implementation of a second environmental chamber positioned around the stage and optics. State of the art environmental chambers with one-sigma air temperature stability of a few milli-degree Celsius at a single point have been demonstrated [8]. Implementing a similar system may further reduce the environmental variation error.

The uncertainty due to misalignment may also be reduced by adding a longer (approximately 1 m) secondary precision slide to the measurement setup, e.g., an air bearing system. In this design, the smaller positioning system would be mounted to the carriage of the air bearing slide via a wobble plate used for adjusting and aligning the travel of the smaller axis to the travel of the longer axis. Alignment of the two axes would be achieved by aligning each to an intermediate straightedge artifact with a low uncertainty displacement sensor, e.g., capacitance probe. The laser beam could then be aligned using the full travel of the longer axis. Substituting the travel of the shorter axis, 50 mm, with the travel of the longer axis, 1 m, in

Eq. 18, results in alignment angle, γ , of approximately 6 arc seconds and an uncertainty due to misalignment, u_{MA} , of 0.01 nm.

Last, manufacturing this class of stage from materials with low coefficients of thermal expansion will also help decrease the measurement uncertainty. For example, a list of suitable materials may include Silicon Carbide, Invar, and Zerodur, to name a few. Implementation of these materials would further reduce the standard uncertainty in compensating for E_{VE} to 0.8 nm, 0.5 nm, and 0.02 nm, respectively. The resulting expanded uncertainty for unidirectional repeatability due to each material would then be 3.2 nm, 2.0 nm, and 0.1 nm, respectively.

CLOSING REMARKS

A preliminary uncertainty analysis has been performed to highlight the challenges and identify the sources of error in measuring the linear positioning performance of this class of linear positioning system. Suggestions for reducing measurement uncertainty were provided. Future work will involve advancing our measurement capabilities to better measure all sources of error and to further reduce their individual contributions to the combined measurement uncertainty.

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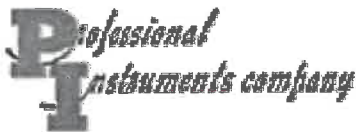


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